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Neutrinos: DRAFT

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Subgroup Conveners:

1.1 Introduction

Neutrinos are the most elusive of the known fundamental particles. They are color-neutral and charge-neutral spin one-half fermions, and, to the best of our knowledge, only interact with charged fermions and massive gauge bosons, through the weak interactions. For this reason, neutrinos can only be observed and studied because there are very intense neutrino sources (natural and artificial) and only if one is willing to work with large detectors.

The existence of neutrinos was postulated in the early 1930s, but they were only first observed in the 1950s. The third neutrino flavor eigenstate, the tau-type neutrino ν_τ, was the last of the fundamental matter particles to be observed [**?**], eluding direct observation six years longer than the top quark [**?**, **?**]. More relevant to this chapter, in the late 1990s the discovery of non-zero neutrino masses moved the study of neutrino properties to the forefront of experimental and theoretical particle physics.

Experiments with solar [**?**, **?**, **?**, **?**, **?**, **?**], atmospheric [**?**, **?**], reactor [**?**, **?**] and accelerator [**?**, **?**] neutrinos have established, beyond reasonable doubt, that a neutrino produced in a well-defined flavor state (say, a muon-type neutrino ν_μ) has a non-zero probability of being detected in a different flavor state (say, an electron-type neutrino ν_e). This flavor-changing probability depends on the neutrino energy and the distance traversed between the source and the detector. The simplest and only consistent explanation of all neutrino data collected over the last two decades is a phenomenon referred to as 'neutrino mass-induced flavor oscillation.' These neutrino oscillations, which will be discussed in more detail in Sec. 1.2, in turn imply that neutrinos have nonzero masses and neutrino mass eigenstates are different from neutrino weak eigenstates, *i.e.*, leptons mix.

In a nutshell, if the neutrino masses are distinct and leptons mix, a neutrino can be produced, via weak interactions, as a coherent superposition of mass-eigenstates, e.g., a neutrino ν_α with a well-defined flavor, and has a non-zero probability to be measured as a neutrino ν_β of a different flavor ($\alpha, \beta = e, \mu, \tau$). The oscillation probability $P_{\alpha\beta}$ depends on the neutrino energy E, the propagation distance L, and on the neutrino mass-squared differences, $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$, $i, j = 1, 2, 3, \ldots$, and the elements of the leptonic mixing matrix,[1] U, which relates neutrinos with a well-defined flavor (ν_e, ν_μ, ν_τ) and neutrinos with a well-defined mass ($\nu_1, \nu_2, \nu_3, \ldots$). For three neutrino flavors, the elements of U are defined by

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}. \tag{1.1}$$

Almost all neutrino data to date can be explained assuming that neutrinos interact as prescribed by the Standard Model, there are only three neutrino mass eigenstates, and U is unitary. Under these circumstances, it is customary to parameterize U in Eq. (1.1) with three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ and three complex phases, δ, ξ, ζ, defined by

$$\frac{|U_{e2}|^2}{|U_{e1}|^2} \equiv \tan^2\theta_{12}; \qquad \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2} \equiv \tan^2\theta_{23}; \qquad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}, \tag{1.2}$$

with the exception of ξ and ζ, the so-called Majorana CP-odd phases. These are only physical if the neutrinos are Majorana fermions, and have essentially no effect in flavor-changing phenomena.

In order to relate the mixing elements to experimental observables, it is necessary to properly define the neutrino mass eigenstates, *i.e.*, to "order" the neutrino masses. This is done in the following way: $m_2^2 > m_1^2$ and $\Delta m^2_{21} < |\Delta m^2_{31}|$. In this case, there are three mass-related oscillation observables: Δm^2_{21} (positive-definite), $|\Delta m^2_{31}|$, and the sign of Δm^2_{31}. A positive (negative) sign for Δm^2_{31} implies $m_3^2 > m_2^2$ ($m_3^2 < m_1^2$)

[1]Often referred to as the Maki-Nakagawa-Sakata (MNS) Matrix, or the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix.

and characterizes a so-called normal (inverted) neutrino mass hierarchy. The two mass hierarchies are depicted in Fig. 1-1.

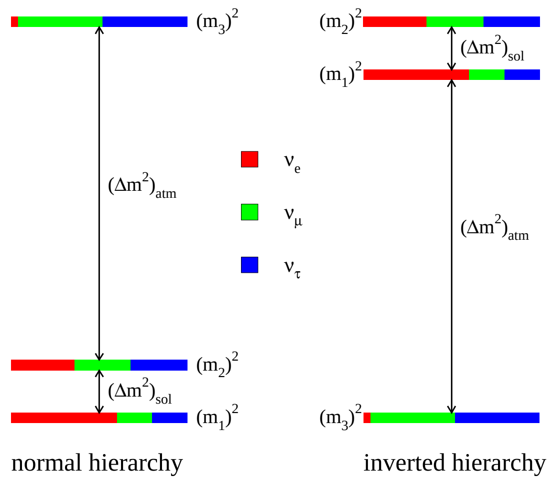


Figure 1-1. *Cartoon of the two distinct neutrino mass hierarchies that fit all of the current neutrino data, for fixed values of all mixing angles and mass-squared differences. The color coding (shading) indicates the fraction $|U_{\alpha i}|^2$ of each distinct flavor ν_α, $\alpha = e, \mu, \tau$ contained in each mass eigenstate ν_i, $i = 1, 2, 3$. For example, $|U_{e2}|^2$ is equal to the fraction of the $(m_2)^2$ "bar" that is painted red (shading labeled as "ν_e").*

Our knowledge of neutrino oscillation parameters has evolved dramatically over the past two decades. As summarized in Sec. 1.4, all three mixing angles have been measured relatively well, along with (the magnitude of) the mass-squred difference. On the other hand, we have virtually no information concerning δ (and, for that matter, ξ and ζ) or the sign of Δm^2_{31}. We also don't know the value of the neutrino masses themselves – only differences of the masses-squared. We can't rule out the possibility that the lightest neutrino is virtually massless ($m_{\rm lightest} \ll 10^{-3}$ eV) or that all neutrino masses are virtually the same (e.g. $m_1 \sim m_2 \sim m_3 \sim 0.1$ eV). Probes outside the realm of neutrino oscillations are required to investigate the values of the neutrino masses. These are described in Sec. 1.6.

One of the main goals of next-generation experiments is to test whether the scenario outlined above, the standard three-massive-neutrinos paradigm, is correct and complete. This can be achieved by next-generation experiments sensitive to neutrino oscillations via not simply determining all of the parameters above, but by "over-constraining" the parameter space in order to identify potential inconsistencies. This is far from a simple task, and the data collected thus far, albeit invaluable, allow for only the simplest consistency checks. Precision measurements, as will be discussed in Sec. 1.4, will be required.

Currently, large, qualitative modifications to the standard paradigm are allowed. Furthermore, there are several, none too significant, hints in the world neutrino data that point to a neutrino sector that is more complex than the one outlined above. These will be discussed in Sec. 1.8. Possible surprises include new, gauge singlet fermion states that manifest themselves only by mixing with the known neutrinos, and new weaker-than-weak interactions.

Another issue of fundamental importance is the investigation of the status of CP-invariance in leptonic processes. Currently, all observed CP-invariance violating phenomena are governed by the single physical CP-odd phase parameter in the quark mixing matrix. Searches for other sources of CP-invariance violation, including the so-called strong CP-phase θ_{QCD}, have, so far, failed. The picture currently emerging from neutrino oscillation data allow for a completely new, independent source of CP-invariance violation. The

CP-odd parameter δ, if different from zero or π, implies that neutrino oscillating probabilities violate CP-invariance, i.e., the values of the probabilities for neutrinos to oscillate are different from those of antineutrinos! We describe this phenomenon in more detail in Secs. 1.2, 1.4.

It should be noted that, if neutrinos are Majorana fermions, the CP-odd phases ξ and ζ also mediate CP-invariant violating phenomena [**?**] (alas, we don't yet really know how to study these in practice). In summary, if neutrinos are Majorana fermions, the majority of CP-odd parameters in particle physics — even in the absence of other new physics — belong to the lepton sector. These are completely unknown and can "only" be studied in neutrino experiments. Neutrino oscillations provide a unique opportunity to revolutionize our understanding of CP-invariance violation, with potentially deep ramications for both particle physics and cosmology.

In the Standard Model, neutrinos were predicted to be exactly massless. The discovery of neutrino masses hence qualifies as the first instance where the Standard Model failed. This is true even if the three-massive-neutrino paradigm described above turns out to be the whole story. More important is the fact that all modifications to the Standard Model that lead to massive neutrinos change it qualitatively. For a more detailed discussion of this point see, for example, [**?**].

Neutrino masses, while non-zero, are tiny when compared to all other known fundamental fermion masses in the Standard Model, as depicted in Fig. 1-2. Two features readily stand out: (i) neutrino masses are at least six orders of magnitude smaller than the electron mass, and (ii) there is, to the best of our knowledge, a "gap" between the largest allowed neutrino mass and the electron mass. We don't know why neutrino masses are so small or why there is such a large gap between the neutrino and the charged fermion masses. We suspect, however, that this may be Nature's way of telling us that neutrino masses are "different."

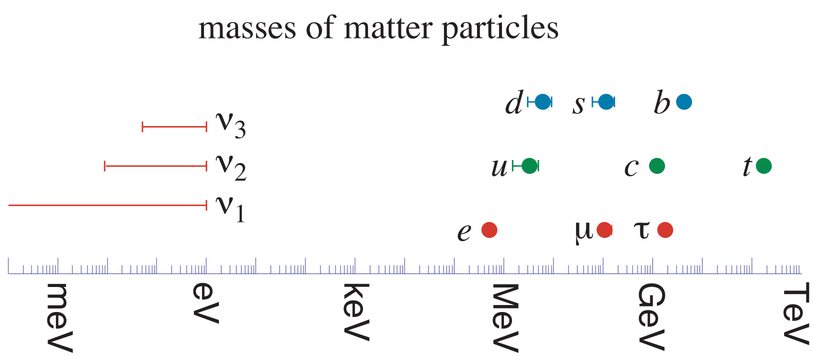


Figure 1-2. *Standard Model fermion masses. For the neutrino masses, the normal mass hierarchy was assumed, and a loose upper bound $m_i < 1$ eV, for all $i = 1, 2, 3$ was imposed.*

This suspicion is only magnified by the possibility that massive neutrinos, unlike all other fermions in the Standard Model, may be Majorana fermions. The reason is simple: neutrinos are the only electrically neutral fundamental fermions and hence need not be distinct from their antiparticles. Determining the nature of the neutrino – Majorana or Dirac – would not only help guide theoretical work related to uncovering the origin of neutrino masses, but could also reveal that the conservation of lepton number is not a fundamental law of Nature. The most promising avenue for learning the fate of lepton number, as will be discussed in Sec. 1.5, is to look for neutrinoless double-beta decay, a lepton-number violating nuclear process. The observation of a non-zero rate for this hypothetical process would easily rival, as far as its implications for our understanding of nature are concerned, the first observations of parity violation and CP-invariance violation in the mid-twentieth century.

It is natural to ask what augmented, "new" Standard Model (νSM) leads to non-zero neutrino masses. The answer is that we are not sure. There are many different ways to modify the Standard Model in order to accommodate neutrino masses. While these can differ greatly from one another, all succeed – by design – in explaining small neutrino masses and all are allowed by the current particle physics experimental data. The most appropriate question, therefore, is not what are the candidate νSM's, but how can one identify the "correct" νSM? The answers potentially lie in next-generation neutrino experiments, which are described throughout this chapter.

Before discussing concrete examples, it is important to highlight the potential theoretical significance of nonzero neutrino masses. In the standard model, the masses of all fundamental particles are tied to the phenomenon of electroweak symmetry breaking and a single mass scale – the vacuum expectation value of the Higgs field. Nonzero neutrino masses may prove to be the first direct evidence of either a new mass scale, completely unrelated to electroweak symmetry breaking, or evidence that electroweak symmetry breaking is more complex than dictated by the standard model.

Here we discuss one generic mechanism in more detail. The effect of heavy new degrees of freedom in low-energy phenomena can often be captured by adding to the Standard Model higher-dimensional operators. As first pointed out in [**?**], given the Standard Model particle content and gauge symmetries, one is allowed to write only one type of dimension-five operator – all others are dimension-six or higher:

$$\frac{1}{\Lambda}\,(LH)(LH) + h.c. \quad \Rightarrow \quad \frac{v^2}{\Lambda}\nu\nu + h.c., \tag{1.3}$$

where L and H are the lepton and Higgs boson $SU(2)_L$ doublets, and the arrow indicates one of the components of the operator after electroweak symmetry is broken. v is the vacuum expectation value of the neutral component of H, and Λ is the effective new physics scale. If this operator is indeed generated by some new physics, neutrinos obtain Majorana masses $m_\nu \sim v^2/\Lambda$. For $\Lambda \sim 10^{15}$ GeV, $m_\nu \sim 10^{-1}$ eV, in agreement with the current neutrino data. This formalism explains the small neutrino masses via a seesaw mechanism: $m_\nu \ll v$ because $\Lambda \gg v$.

Λ is an upper bound for the masses of the new particles that lead to Eq. (1.3). If the new physics is strongly coupled and Eq. (1.3) is generated at the tree-level, the new degrees of freedom are super-heavy: $M_{\rm new} \sim 10^{15}$ GeV. If, however, the new physics is weakly coupled or Eq. (1.3) is generated at the loop level, virtually any value for $M_{\rm new} \gtrsim 1$ eV is allowed. In summary, if Eq. (1.3) is correct, we expect new physics to show up at a new mass scale $M_{\rm new}$ which lies somewhere between 10^{-9} GeV and 10^{15} GeV. Clearly, more experimental information is required.

At the tree-level, there are only three renormalizable extensions of the Standard Model that lead to Eq. (1.3). They are referred to as the three types of seesaw mechanisms, and are summarized as follows. For more details, see, for example, [**?**, **?**].

- *Type I* [**?**, **?**, **?**, **?**, **?**]: The fermion sector of the Standard Model is augmented by at least two gauge singlets N_i, which couple to the lepton and Higgs scalar doublets via a new Yukawa coupling y_ν. These so-called right-handed neutrinos are allowed to have Majorana masses M_N. After electroweak symmetry breaking, assuming $M_N \gg y_\nu v$, one generates Eq. (1.3). Here $\Lambda = M_N/y_\nu^2$.
- *Type II* [**?**, **?**, **?**, **?**, **?**]: The Higgs sector of the Standard Model is extended by one $SU(2)_L$ Higgs triplet Δ. The neutrino masses are $m_\nu \approx Y_\nu v_\Delta$, where v_Δ is the vacuum expectation value (vev) of the neutral component of the triplet and Y_ν is the Yukawa coupling that describes the strength of the Δ coupling to two lepton doublets. If the doublet and triplet mix via a dimensionful parameter μ, electroweak symmetry breaking can translate into $v_\Delta \sim \mu v^2/M_\Delta^2$, where M_Δ is the mass of the triplet. In this case, after one integrates out the Δ states Eq. (1.3) is generated, and $\Lambda = M_\Delta^2/(\mu Y_\nu)$. Small neutrino masses require either $M_\Delta \gg v$ or $\mu \ll v$.

- *Type III* [**?**]: The fermion sector of the Standard Model is augmented by at least two $SU(2)_L$ triplets T_i with zero hypercharge. As in the Type I case, if these triplets couple to the lepton and Higgs scalar doublets via a new Yukawa coupling y_T, and are endowed with Majorana masses M_T, after electroweak symmetry breaking, assuming $M_T \gg y_T v$, one generates Eq. (1.3). Here $\Lambda = M_T/y_T^2$.

We will refer to different manifestations of these scenarios throughout this chapter. Some predict new physics at scales that can be probed at the energy frontier or elsewhere in the intensity frontier, while others predict new physics scales that are way beyond the reach of laboratory experiments. If that turns out to be the case, we will only be able to access the new physics indirectly through neutrino experiments and the study of relics in the cosmic frontier. There are also numerous synergies of neutrinos with other fundamental physics [**?**].

Neutrino data also provide a new piece to the flavor puzzle: the pattern of neutrino mixing. The absolute value of the entries of the CKM quark mixing matrix are, qualitatively, given by

$$|V_{\rm CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}, \tag{1.4}$$

while those of the entries of the PMNS matrix are given by

$$|U_{\rm PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}. \tag{1.5}$$

It is clear that the two matrices look very different. While the CKM matrix is almost proportional to the identity matrix plus hierarchically ordered off-diagonal elements, the PMNS matrix is far from diagonal and, with the possible exception of the U_{e3} element, all elements are $\mathcal{O}(1)$. Significant research efforts are concentrated on understanding what, if any, is the relationship between the quark and lepton mixing matrices and what, if any, is the "organizing principle" responsible for the observed pattern of neutrino masses and lepton mixing. There are several different theoretical ideas in the market (for summaries, overviews and more references see, for example, [**?**, **?**]). Typical results include predictions for the currently unknown neutrino mass and mixing parameters ($\sin^2\theta_{13}$, $\cos 2\theta_{23}$, the mass hierarchy, *etc.*) and the establishment of sum rules involving different parameters. Some of the challenges are discussed in Sec. 1.4

Precision neutrino oscillation measurements are required to address the flavor questions above. That can only be achieved as the result of significant investments in intense, well-characterized neutrino sources and massive high-precision detectors. Some of these are summarized in Sec. 1.3 and spelled out in more detail throughout this Chapter. Excellent understanding of neutrino interactions – beyond the current state of the art – is also mandatory. This will require a comprehensive experimental program on neutrino scattering, as summarized in Sec. 1.7. These, of course, are not only ancillary to neutrino oscillation experiments, but are also interesting in their own right. Neutrinos, since they interact only weakly, serve as a unique probes of nucleon and nuclear properties, and may reveal new physics phenomena at the electroweak scale, including some that are virtually invisible to the Tevatron and the LHC.

(Massive) neutrinos also serve as unique messengers in astrophysics and cosmology, as discused in Sec. 1.9. Astrophysical neutrino searches may uncover indirect evidence for dark matter annihilation in the earth, the sun, or the center of galaxy. Neutrinos produced in supernova explosions contain information from deep within the innards of the exploding stars and their studies may also help reveal unique information regarding neutrino properties. Big Bang neutrinos play a definitive role in the thermal history of the universe. Precision cosmology measurements also may reveal neutrino properties, including the absolute values of the neutrino masses. Finally, the unique character of the neutrinos and the experiments used to study them provide unique opportunities outside the realm of particle physics research. More details along these lines are discussed in Sec. 1.10.

1.2 Overview of Neutrino Oscillations

Physical effects of non-zero neutrino masses, to date, have been observed only in neutrino oscillation experiments. Those are expected to remain, for the foreseeable future, the most powerful tools available for exploring the new physics revealed by solar and atmospheric neutrino experiments at the end of the twentieth century.

The standard setup of a neutrino oscillation experiment is as follows. A detector is located a distance L away from a source, which emits ultra-relativistic neutrinos or antineutrinos with, most often, a continuous spectrum of energies E, and flavor $\alpha = e, \mu$, or τ. According to the Standard Model, the neutrinos interact with matter either via W-boson exchange charged-current interactions where a neutrino with a well-defined flavor ν_α gets converted into a charged lepton of the same flavor ($\nu_e X \to eX'$, *etc.*) or via Z-boson exchange neutral-current interactions, which preserve the neutrino flavor ($\nu_\mu X \to \nu_\mu X'$). The occurrence of a neutral-current process is tagged by observing the system against which the neutrinos are recoiling. The detector hence is capable of measuring the flux of neutrinos or antineutrinos with flavor $\beta = e, \mu$, or τ, or combinations thereof, often as a function of the neutrino energy. By comparing measurements in the detector with expectations from the source, one can infer $P_{\alpha\beta}(L, E)$ or $\bar{P}_{\alpha\beta}(L, E)$, the probability that a(n) (anti)neutrino with energy E produced in a flavor eigenstate ν_α is measured in a flavor ν_β after it propagates a distance L. In practice, it is often preferable to make multiple measurements of neutrinos at different distances from the source, which can be helpful for both the cancellation of systematic uncertainties and for teasing out effects beyond the standard three-flavor paradigm.

In the standard three-flavor paradigm, $P_{\alpha\beta}$ is a function of the mixing angles $\theta_{12,13,23}$, the Dirac CP-odd phase δ, and the two independent neutrino mass-squared differences $\Delta m^2_{21,31}$, defined in the Introduction. Assuming the neutrinos propagate in vacuum, and making explicit use of the unitarity of U, one can express $P_{\alpha\beta}(L, E) = |A_{\alpha\beta}|^2$, where

$$A_{\alpha\beta} = \delta_{\alpha\beta} + U_{\alpha 2}U^*_{\beta 2}\left(\exp\left(-i\frac{\Delta m^2_{21}L}{2E}\right) - 1\right) + U_{\alpha 3}U^*_{\beta 3}\left(\exp\left(-i\frac{\Delta m^2_{31}L}{2E}\right) - 1\right), \tag{1.6}$$

$$\bar{A}_{\alpha\beta} = \delta_{\alpha\beta} + U^*_{\alpha 2}U_{\beta 2}\left(\exp\left(-i\frac{\Delta m^2_{21}L}{2E}\right) - 1\right) + U^*_{\alpha 3}U_{\beta 3}\left(\exp\left(-i\frac{\Delta m^2_{31}L}{2E}\right) - 1\right), \tag{1.7}$$

up to an unphysical overall phase. A ($\bar{A}$) is the amplitude for (anti)neutrino oscillations. It is easy to see that $P_{\alpha\beta}$ are oscillatory functions of L/E with, in general, three distinct, two independent oscillation lengths proportional to Δm^2_{21}, Δm^2_{31} and $\Delta m^2_{32} \equiv \Delta m^2_{31} - \Delta m^2_{21}$, as depicted in Figure 1-3. Ideally, measurements of some $P_{\alpha\beta}$ as a function of L/E would suffice to determine all neutrino oscillation parameters. These would also allow one to determine whether the standard paradigm is correct, *i.e.*, whether Eqs. (1.6,1.7) properly describe neutrino flavor-changing phenomena.

For example, if one could measure both P_{ee} and $P_{\mu\mu}$ as a function of L/E, one should be able to determine not only Δm^2_{21} and $|\Delta m^2_{31}|$, but also $|U_{e2}|^2$, $|U_{e3}|^2$, $|U_{\mu 2}|^2$ and $|U_{\mu 3}|^2$, and the sign of Δm^2_{31}. This in turn would translate into measurements of all mixing parameters, including the CP-odd phase δ. One would also be able to determine, for example, whether there are other oscillation lengths, which would indicate there

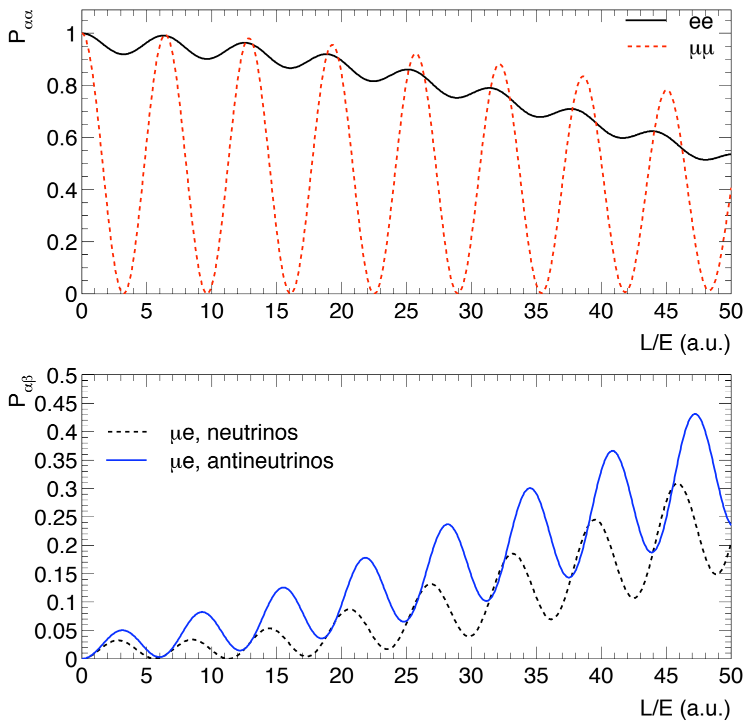


Figure 1-3. *Top: P_{ee} and $P_{\mu\mu}$ in vacuum as a function of L/E (in arbitrary units), for representative values of the neutrino oscillation parameters, including a non-zero value of δ. Bottom: $P_{\mu e}$ and $\bar{P}_{\mu e}$ in vacuum as a function of L/E, for representative values of the neutrino oscillation parameters.*

are new, yet-to-be-observed, neutrino states, or whether $P_{ee,\mu\mu} \neq 1$ in the limit $L \to 0$, which would indicate, for example, the existence of new, weaker-than-weak, charged-current type interactions.

In the real world, such measurements are, to say the least, very hard to perform, for several reasons. Δm^2_{21} is much smaller than the magnitude of $\Delta m^2_{31,32}$, which in turn makes it challenging to observe two independent oscillation frequencies in the same experimental setup. For this reason all measurements of $P_{\mu\mu}$ performed to date are, effectively, only sensitive to $|\Delta m^2_{31}|$ and $|U_{\mu 3}|$ – the L/E factors probed are too small to "see" the Δm^2_{21}-driven oscillations or distinguish Δm^2_{31} from Δm^2_{32}. On the other hand, the magnitude of $|U_{e3}|$ is much smaller than that of the other entries of U. For this reason, measurements of P_{ee} for solar neutrinos have only been precise enough to definitively observe Δm^2_{21}-driven oscillations and hence determine its magnitude, along with that of U_{e2}.

Another real-world issue is that, for any setup, it is not possible to measure any $P_{\alpha\beta}$ with perfect L/E resolution. Furthermore, the available L/E ranges are, in most cases, narrow. More realistically, one expects to measure, with decent statistics and small systematic errors, $P_{\alpha\beta}$ integrated over a few finite-sized L/E bins. This discreteness of the data leads to ambiguities when it comes to measuring the different mixing parameters. For example, different pairs of θ_{13}, δ values lead to identical values for $P_{\alpha\beta}$ integrated over a fixed L/E. The same is true for pairs of θ_{13}, θ_{23}, and so on. A so-called eight-fold degeneracy has been identified and studied in great detail in the neutrino literature (see, for example, [**?**, **?**, **?**]). The solution to this challenge is to perform several measurements of different $P_{\alpha\beta}$ at different values of L and E (and L/E). This is especially true if one is interested in not only measuring the three-flavor neutrino mixing parameters but also, much more importantly, over-constraining the standard paradigm and hence testing its validity.

For example, one would like to precisely measure θ_{13} in different channels, for different values of L and E, to find out if all of them agree.

Measurements of vacuum survival probabilities, $P_{\alpha\alpha}$ or $\bar{P}_{\alpha\alpha}$ do not violate CP invariance: $P_{\alpha\alpha} = \bar{P}_{\alpha\alpha}$ is guaranteed by CPT-invariance. In order to directly observe CP-invariance violation, one needs to measure an appearance probability, say $P_{\mu e}$. $P_{\mu e}$ is different from $\bar{P}_{\mu e}$,[2] as depicted in Fig. 1-3 (bottom), if the following conditions are met, as one can readily confirm by studying Eqs. (1.6,1.7): (i) all $U_{\alpha i}$ have non-zero magnitude, (ii) $U_{\alpha 2}U^*_{\beta 2}$ and $U_{\alpha 3}U^*_{\beta 3}$ are relatively complex, (iii) L/E is large enough that both $\Delta m^2_{21,31} \times L/E$ are significantly different from zero. Given what is known about the oscillation parameters, condition (iii) can be met for any given neutrino source by choosing a large enough value for L. This, in turn, translates into the need for a very intense source and a very large, yet high-precision, detector, given that for all known neutrino sources the neutrino flux falls off like $1/L^2$ for any meaningful value of L. Whether conditions (i) and (ii) are met lies outside the control of the experimental setups. Given our current understanding, including the newly acquired knowledge that $|U_{e3}| \neq 0$, condition (i) holds. That being the case, condition (ii) is equivalent to $\delta \neq 0, \pi$. In the standard paradigm, the existence of CP-invariance violation is entirely at the mercy of the value of CP-odd phase δ, currently unconstrained.

All neutrino data accumulated so far provide only hints for non-zero $P_{\mu\tau}$ [**?**, **?**] and $P_{\mu e}$ [**?**, **?**].[3] Both results are only sensitive to one mass-square difference ($|\Delta m^2_{31}|$) and to $|U_{\mu 3}U_{\tau 3}|$ and $|U_{\mu 3}U_{e3}|$, respectively. The goal of the current neutrino oscillation experiments NOνA and T2K is to observe and study $P_{\mu e}$ and $\bar{P}_{\mu e}$ governed by Δm^2_{31}, aiming at measuring U_{e3} and, perhaps, determining the sign of Δm^2_{31} through matter effects, as will be discussed promptly.

Eqs. (1.6,1.7) are valid only when the neutrinos propagate in a vacuum. When neutrinos propagate through a medium, the oscillation physics is modified by so-called matter effects [**?**]. These are due to the coherent forward scattering of neutrinos with the electrons present in the medium, and they create an additional contribution to the phase differences. Notably, this additional contribution distinguishes between neutrinos and antineutrinos, since there are no positrons present in the Earth.[4] Matter effects also depend on whether the electron neutrino is predominantly made out of the heaviest or lightest mass eigenstates, thus allowing one to address the ordering of the neutrino mass eigenstates. For one mass hierarchy, the oscillation of neutrinos for a certain range of L/E values can be enhanced with respect to that of antineutrinos, while for the other mass hierarchy the effect is reversed. On the flip side, if the mass hierarchy is not known, matter effects lead to ambiguities in determining the oscillation parameters, as discussed briefly earlier. Matter effects have already allowed the determination of one "mass hierarchy," that of ν_1 and ν_2. Thanks to matter effects in the sun, we know that ν_1, which is lighter than ν_2, has the larger electron component: $|U_{e1}|^2 > |U_{e2}|^2$. A similar phenomenon should be observable in the Δm^2_{31} sector, given the recent discovery that $|U_{e3}|$ is not zero. Quantitatively, the importance of matter effects will depend on the density of the medium being traversed, which determines the so-called matter potential $A \equiv \sqrt{2}G_F N_e$, where G_F is the Fermi constant and N_e is the electron number-density of the medium, and on the value of $\Delta m^2_{21,31}/E$. Matter effects are irrelevant when $A \ll \Delta m^2_{21,31}/E$. For $\Delta m^2_{31(21)}$ matter effects in the Earth's crust are significant for $E \gtrsim 1$ GeV (20 MeV).

[2] Note that T-invariance violation, $P_{e\mu} \neq P_{\mu e}$, is also present under the same conditions.

[3] Solar data translate into overwhelming evidence for $P_{e\mu} + P_{e\tau} \neq 0$. In the standard paradigm, this is indistinguishable from $1 - P_{ee} \neq 1$ and hence cannot, even in principle, provide more information than a disappearance result.

[4] In fact, the electron background explicitly violates CPT symmetry. For neutrinos oscillating in matter, it is no longer true, for example, that $P_{\alpha\alpha} = \bar{P}_{\alpha\alpha}$.

1.3 Neutrino Experiments: Sources and Detectors

Next-generation experiments have at their disposal a handful of neutrino sources, which we describe qualitatively here, concentrating on their prospects for neutrino oscillation searches. The sources span many orders of magnitude in energy: see Fig. 1-4. Associated with each experiment is an appropriate detector. The natures and the capabilities of the detectors depend on the neutrino source.

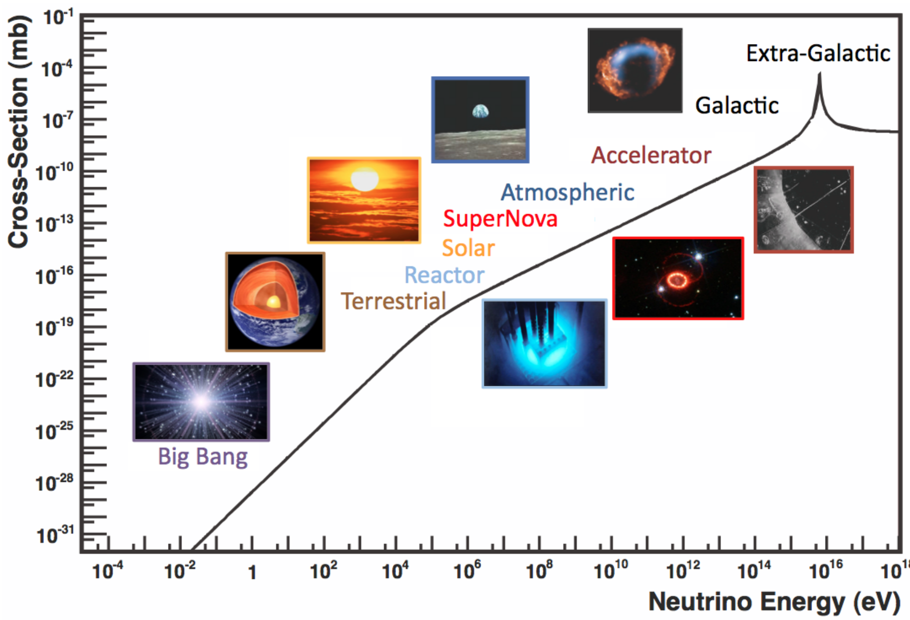


Figure 1-4. *Neutrino interaction cross section as a function of energy, showing typical energy regimes for different sources. The scattering cross section for $\bar{\nu}_e\, e^- \to e^-\, \bar{\nu}_e$ on free electrons is shown for comparison. Plot is reproduced from [?].*

The sun is a very intense source of ν_e with energies between 100 keV and 10 MeV. Precision measurements of the low-energy component of the solar neutrino flux (the so-called *pp*-neutrinos) may provide an unique opportunity to improve on the precision with which $\sin^2\theta_{12}$ is known [?]. The detection of very low-energy solar neutrinos is very challenging, but R&D related to building such detectors profits from significant synergy with efforts to look for dark matter and observe neutrinoless double-beta decay. Solar neutrinos in the few-MeV range are very sensitive to solar matter effects, and provide a unique opportunity to test the Standard Model through the Mikheev-Smirnov-Wolfenstein (MSW) matter effect [?, ?]. Indeed, data from the SNO experiment seem to hint at potential deviations from Standard Model expectations [?]. During this decade, more (neutrino) light is expected to shine on this potentially very important matter, from the Borexino [?] and the SNO+ [?] experiments.

Nuclear reactors are an intense, very pure source of $\bar{\nu}_e$ with energies between a few and several MeV. Due to the low neutrino energies, only $\bar{\nu}_e$ can be detected in the final state, which is done via inverse β-decay, $\bar{\nu}_e + p \to e^+ + n$. The current generation of reactor experiments aims at percent-level measurements of the $\bar{\nu}_e$ spectrum, one or two kilometers away from the source. At these distances and energies one is sensitive only to Δm^2_{31}-driven oscillations. The necessary precision is expected to be achieved through the comparison of data obtained at near and far detectors. In a nutshell, the near detector measures the neutrino flux before oscillations have had time to act, while the far detector measures the effects of the oscillations [?]. Reactor neutrino experiments with much longer baselines (say, 50 km) have been considered: see, for example, [?, ?]. These would be sensitive to both Δm^2_{31} and Δm^2_{21}-driven oscillations, and, in principle, would allow much more precise measurements of Δm^2_{21} and $|U_{e2}|$. A detector with exquisite energy resolution may also be sensitive to the neutrino mass hierarchy (see, for example, [?]). A concrete proposal for 10 km reactor neutrino experiment, Daya Bay II, is currently under serious consideration in China [?].

Meson decays are a very good source of ν_μ and ν_τ and their antiparticles. The heavy τ-lepton mass, however, prevents any realistic means of producing anything that would qualify as a ν_τ-beam, so we will only discuss ν_μ beams. Pions and, to a lesser extent, kaons are produced in large numbers through proton–nucleus interactions. These, in turn, can be sign-selected in a variety of ways to yield a mostly pure ν_μ or $\bar{\nu}_\mu$ beam. The neutrino energy is directly related to the pion energy.

The lowest energy ν_μ "beams" (really, isotropic sources) are achieved from pion decay at rest. A large sample of mostly π^+ at rest yields a very well-characterized flux of mono-energetic ν_μ (from the π^+ decay), along with $\bar{\nu}_\mu$ and ν_e from the subsequent daughter muon decay. All neutrino energies are below the muon production threshold, so only ν_e and $\bar{\nu}_e$ can be detected via charged-current interactions. An interesting experimental strategy is to search for $\bar{\nu}_e$ via inverse β-decay, a very well understood physics process, and hence measure with good precision $\bar{P}_{\mu e}$ [?]. Matter effects play an insignificant role for the decay-at-rest beams, rendering oscillation results less ambiguous. On the other hand, even very precise measurements of $\bar{P}_{\mu e}$ from pion decay at rest are insensitive to the neutrino mass hierarchy.

Boosted pion-decay beams are the gold standard of readily accessible neutrino oscillation experiments. A pion beam is readily produced by shooting protons on a target. These can be charge- and energy-selected, yielding a beam of either mostly ν_μ or $\bar{\nu}_\mu$. Larger neutrino energies allow one to look for ν_e, ν_μ and, for energies above a few GeV, ν_τ in the far detector. Large neutrino energies, in turn, require very long baselines[5] and hence very intense neutrino sources and very large detectors. Intense neutrino sources, in turn, require very intense proton sources, of the type described in Sec. 1.3. For this reason, these pion-decay-in-flight beams are often referred to as superbeams. Larger neutrino energies and longer baselines also imply nontrivial matter effects even for Δm^2_{31}-driven oscillations. A neutrino beam with energies around 1 GeV and baselines around 1000 km will allow the study of $P_{\mu\mu}$ and $P_{\mu e}$ (and, in principle, the equivalent oscillation probabilities for antineutrinos) as long as the far detector is sensitive to both ν_μ and ν_e charged-current interactions. One may choose to observe the neutrino flux a few degrees off the central beam axis, where the pion decay kinematics result in a narrowly peaked neutrino spectrum. This is beneficial for optimizing sensitivity at the oscillation maximum and for reducing backgrounds outside the energy regime of interest.

The constant collision of cosmic rays with the atmosphere produces mesons (mostly pions and kaons) and, upon their decays, ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$. These atmospheric neutrinos cover a very wide energy range (100 MeV to 100 GeV and beyond) and many different distances (15 km to 13000 km), some going through the core of the Earth and hence probing matter densities not available for Earth-skimming neutrino beams. This is, by far, the broadest (in terms of L/E range) neutrino "beam." As far as challenges are concerned, uncertainties in the atmospheric neutrino flux are not small, and the incoming neutrino energy and direction must be reconstructed only with information from the neutrino detector.

In the past, atmospheric neutrinos have provided the first concrete evidence for neutrino oscillations, and at present they are still a major contributor to the global fits to neutrino oscillation parameters. They will continue to be important in the future. They are also ubiquitous and unavoidable. IceCube DeepCore is already taking data and will accumulate close to a million events with energies above about 10 GeV over the next decade [?]. Any other very large detector associated with the intensity frontier program will also collect a large number of atmospheric neutrino events in various energy ranges, through different types of signatures. While atmospheric neutrino data suffer from larger systematic uncertainties, some of these can

[5] The oscillation phase scales like L/E. For a 1 GeV beam, one aims at L values close to 1000 km.

be greatly reduced by studying angular and energy distributions of the very high statistics data. Their study can complement that of the high precision measurements from fixed baseline experiments. For example, non-standard interactions of neutrinos, additional neutrino flavors and other new physics phenomena affecting neutrinos could be present, and their effects are likely to be more important at higher energies or in the presence of matter, thus making atmospheric neutrinos an ideal testing ground (see, for example, [?]). Furthermore, a precise, very high statistics measurement of the atmospheric neutrino flux itself over a very large range of energies will also contribute to a better understanding of cosmic ray propagation through the atmosphere [?, ?, ?].

Muon decays are also excellent sources of neutrinos. The physics and the kinematics of muon decay are very well known and yield two well-characterized neutrino beams for the price of one: $\nu_\mu + \bar{\nu}_e$ in case of μ^- decays, $\bar{\nu}_\mu + \nu_e$ in the case of μ^+. A neutrino factory is a storage ring for muons with a well-defined energy. Depending on the muon energy, one can measure, with great precision, $P_{\mu\mu}$ and $P_{e\mu}$, assuming the far detector can tell positive from negative muons, potentially along with $P_{\mu e}$ and P_{ee}, if the far detector is sensitive to electron charged-current events and can deal with the π^0 backgrounds, or $P_{\mu\tau}$ and $P_{e\tau}$, if the muon energy is large enough and if the far detector has the ability to identify τ-leptons with enough efficiency. Neutrino factories are widely considered the ultimate sources for neutrino oscillation experiments [?], and probably allow for the most comprehensive tests of the standard three-neutrino paradigm.

Finally, nuclei that undergo β-decay serve as a very well-characterized source of ν_e or $\bar{\nu}_e$. An intense, highly boosted beam of β-decaying nuclei would allow for the study of $P_{e\mu}$. Such sources are known as "β-beams" [?].

To do neutrino experiments, one must of course detect neutrinos. Neutrino detectors span a huge range of technologies, some standard for particle physics and others highly specialized. Detectors are typically quite large, up to multi-kton scale and higher, due to the smallness of neutrino-interaction cross sections. Specific detector needs depend on neutrino energy and physics goals. In general, good reconstruction capabilities, *i.e.* ability to reconstruct momenta and particle types of interaction products, are needed. For long-baseline beams and atmospheric neutrinos, for which energies are high ($\sim$GeV), a variety of tracking detector technologies can be used, each with pros and cons. Commonly-employed detector technologies include segmented trackers (*e.g.* Soudan, MINOS, NOνA, INO), water Cherenkov detectors (Super-K, Hyper-K), and liquid argon time projection chambers (Icarus, LBNE). At the very highest energies, astrophysical neutrino detectors employ enormous volumes of water or ice (IceCube, Antares). For low-energy neutrinos (few to tens of MeV neutrinos from the Sun, reactors, supernovae, stopped-pion sources), homogeneous volumes of liquid scintillator are frequently employed (Borexino, KamLAND, LENA). For the lowest-energy interaction products, dark-matter WIMP detector technology sensitive to nuclear recoils can be used (see Secs. ??).

Many R&D activities related to neutrino detection are currently underway [?]. For neutrino beam sources experiments, for which neutrinos can be easily separated from cosmogenic backgrounds because they tend to arrive in sharp bursts associated with beam pulses, surface detectors are possible. However for physics involving natural neutrinos or steady-state sources, backgrounds become critical. Siting underground, away from cosmic rays, then becomes essential. [?].

Tables 1-1 and 1-2 summarize the capabilities of current and future neutrino-oscillation experiments.

Table 1-1. *Types of current or proposed neutrino oscillation experiments, with some current and future examples (not exhaustive), along with their accessibility to different oscillation channels. $\surd\surd$ indicates the most important oscillation channel(s) while $\surd$ indicates other accessible channels. '$\nu_{e,\mu}$ disapp' refers to the disappearance of ν_e or ν_μ, which are related to P_{ee} and $P_{\mu\mu}$, respectively. '$\nu_\mu \leftrightarrow \nu_e$' refers to the appearance of ν_e in a ν_μ beam or vice versa, related to $P_{e\mu}$ or $P_{\mu e}$. 'ν_τ app' refers to the appearance of ν_τ from an initial state ν_e or ν_μ, related to $P_{(e,\mu)\tau}$. 'Pion DAR/DIF' refers to neutrinos from pion decay at rest or in flight. 'μ DAR/DIF' and 'β Beam' refer to neutrinos from muon decay and nuclear decay in flight, respectively. In particular Pion DIF stands for a so-called conventional neutrino beam. 'Coherent ν-A' stands for very low-energy neutrino experiments, usually from spallation sources, aiming at measuring coherent neutrino–nucleus scattering. See text for more details.*

Expt. Type	ν_e disapp	ν_μ disapp	$\nu_\mu \leftrightarrow \nu_e$	ν_τ app[1]	Examples
Reactor	$\surd\surd$	–	–	–	KamLAND, Daya Bay, Double Chooz, RENO
Solar[2]	$\surd\surd$	–	$\surd$	–	Super-K, Borexino, SNO+, LENS, Hyper-K (prop)
Supernova[3]	$\surd\surd$	$\surd$	$\surd\surd$	–	Super-K, KamLAND, Borexino, IceCube, LBNE (prop), Hyper-K (prop)
Atmospheric	$\surd$	$\surd\surd$	$\surd$	$\surd$	Super-K, LBNE (prop), INO (prop), IceCube, Hyper-K (prop)
Pion DAR	$\surd$	–	$\surd\surd$	–	DAEδALUS
Pion DIF	–	$\surd\surd$	$\surd\surd$	$\surd$	MiniBooNE, MINERνA[4], MINOS(+, prop), T2K NOνA, MicroBooNE, LBNE (prop), Hyper-K (prop)
Coherent ν–A[5]	–	–	–	–	CENNS (prop), CSISNS (prop), Ricochet (prop)
μ DIF[6]	$\surd$	$\surd\surd$	$\surd\surd$	$\surd$	NuStorm, NuFact
β Beam	$\surd$	–	$\surd\surd$	–	

[1]In order to observe ν_τ appearance, a dedicated detector or analysis is required, along with a high-enough neutrino energy. [2]Solar neutrino experiments are sensitive, at most, to the ν_e and the $\nu_e + \nu_\mu + \nu_\tau$ components of the solar neutrino flux. [3]Signatures of neutrino oscillation occurring both in the collapsed star matter and in the Earth will be present in the spectra of observed fluxes of different flavors, and do not strictly fall in these categories; detectors are sensitive to ν_e and $\bar{\nu}_e$ fluxes, and to all other flavors by NC interactions. [4]MINERνA measures neutrino cross sections with the aim of reducing systematics for oscillation experiments. [5]Coherent elastic neutrino-nucleus scattering is purely NC and not sensitive to oscillation between active flavors. [6]The "standard" high-energy neutrino factory setups are not sensitive to electron appearance or disappearance.

Table 1-2. *Types of current or proposed neutrino oscillation experiments and their ability to address some of the outstanding issues in neutrino physics. 'NSI' stands for non-standard neutrino interactions, while ν_s (s for sterile neutrino) stands for the sensitivity to new neutrino mass eigenstates. '$\star\star\star$' indicates a very significant contribution from the current or proposed version of these experimental efforts, '$\star\star$' indicates an interesting contribution from current or proposed experiments, or a significant contribution from a next-next generation type experiment, '$\star$' indicates a marginal contribution from the current or proposed experiments, or an interesting contribution from a next-next generation type experiment. See Table 1-1 and text for more details.*

Expt. Type	$\sin^2\theta_{13}$	$\text{sign}(\Delta m^2_{31})$	δ	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	Δm^2_{21}	NSI	ν_s
Reactor	$\star\star\star$	$\star$	–	–	$\star$	$\star\star$	$\star\star$	–	$\star\star$
Solar	$\star$	–	–	–	–	$\star\star\star$	$\star$	$\star\star$	$\star\star$
Supernova	$\star$	$\star\star\star$	–	–	–	$\star$	$\star$	$\star\star$	$\star\star$
Atmospheric	$\star\star$	$\star\star$	$\star\star$	$\star\star$	$\star\star$	–	–	$\star\star\star$	$\star\star$
Pion DAR	$\star\star\star$	–	$\star\star\star$	$\star$	$\star\star$	$\star$	$\star$	–	$\star\star$
Pion DIF	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star$	$\star$	$\star$	$\star\star$	$\star\star$
Coherent ν–A	–	–	–	–	–	–	–	$\star\star\star$	$\star\star$
μ DIF	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\star$	$\star$	$\star\star$	$\star\star$
β Beam	$\star\star\star$	–	$\star\star\star$	$\star\star$	$\star\star$	$\star$	$\star$	–	$\star\star$

1.4 The Standard Oscillation Paradigm

The three-flavor oscillation framework is quite successful in accounting for a large number of results obtained in very different contexts: the transformation of ν_e into $\nu_{\mu,\tau}$ from the Sun [?]; the disappearance of ν_μ and $\bar{\nu}_\mu$ from neutrinos produced by cosmic ray interactions in the atmosphere; the disappearance of ν_μ and $\bar{\nu}_\mu$ [?, ?] from neutrino beams over distances from 200-740 km [?, ?, ?]; the disappearance of $\bar{\nu}_e$ from nuclear reactors over a distance of about 160 km [?]; the disappearance of $\bar{\nu}_e$ from nuclear reactors over a distance of about 2 km [?, ?, ?]; and at somewhat lower significance also the appearance of ν_e [?, ?] and, at even lower significance, the appearance of ν_τ [?] has been observed in experiments using man-made neutrino beams over 200-740 km distance. All these experimental results can be succinctly and accurately described by the oscillation of three active neutrinos governed by the following parameters, including their $1\,\sigma$ ranges [?]

$$\Delta m^2_{21} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\,\mathrm{eV}^2\,, (3.2\%) \qquad \Delta m^2_{31} = 2.43^{-0.06}_{+0.1} \times 10^{-3}\,\mathrm{eV}^2\,, (3.3\%) \tag{1.8}$$

$$\sin^2\theta_{12} = 3.07^{+0.18}_{-0.16} \times 10^{-1}\,, (16\%) \qquad \sin^2\theta_{23} = 3.86^{+0.24}_{-0.21} \times 10^{-1}\,, (21\%) \tag{1.9}$$

$$\sin^2\theta_{13} = 2.41 \pm 0.25 \times 10^{-1}\,, (10\%) \qquad \delta = 1.08^{+0.28}_{-0.31}\,\mathrm{rad}\,, (27\%)\,, \tag{1.10}$$

where for all parameters whose value depends on the mass hierarchy, we have chosen the values for the normal mass ordering. The choice of parametrization is guided by the observation that for those parameters the χ^2 in the global fit is approximately Gaussian. The percentages given in parenthesis indicate the relative error on each parameter. For the mass splitting we reach errors of a few percent; however, for all of the mixing angles and the CP phase the errors are in the 10-30% range. Therefore, while three-flavor oscillation is able to describe a wide variety of experiments, it would seem premature to claim that we have entered the era of precision neutrino physics or that we have established the three-flavor paradigm at a high level of accuracy. This is also borne out by the fact that there are significant hints at short baselines for a fourth neutrino [?]. Also, more general, so-called non-standard interactions are not well constrained by neutrino data; for a recent review on the topic see Ref. [?]. The issue of what may exist beyond three-flavor oscillations will be discussed in detail in Sec. 1.8 of this report.

Once one realizes that the current error bars are uncomfortably large, the next question is: how well do we want/need to determine the various mixing parameters? The answer can be given at two distinct levels. One is a purely technical one – if I want know X to a precision of x, I need to know Y with a precision of y; an example is, where Y is given by θ_{13} and X could be the mass hierarchy. The answer, at another level, is driven by theory expectations of how large possible phenomenological deviations from the three-flavor framework could be. In order to address the technical part of the question, one first has to define the target precision from a physics point of view. Guidance from other subareas of particle physics reveal that the "target precision" evolves over time. For example, history shows that theoretical estimates of the top quark mass from electroweak precision data and other indirect observable, before its eventual discovery, seem to have been, for the most part (and with very large uncertainties), only several GeV ahead of the experimental reach – at the time, there always was a valid physics argument for why the top quark is "just around the corner." A similar "evolution" of theoretical expectations can be observed in, for example, searches for new phenomena in quark flavor physics. Thus, any argument based on model-building-inspired target precisions is always of a preliminary nature, as our understanding of models evolves over time. With this caveat in mind, one argument for a target precision can be based on a comparison to the quark sector. Based on a theoretical guidance from Grand Unification, one would expect that the answer to the flavor question should find a concurrent answer for leptons and quarks. Therefore, a test of such a models is most sensitive if the precision in the lepton and quark sector is comparable. For instance, the CKM angle γ, which is a very close analog of δ in the neutrino sector, is determined to $(70.4^{+4.3}_{-4.4})^\circ$ [?] and thus, a precision target for δ of roughly 5° would follow.

A different argument for a similar level of precision can be made based on the concept of so-called neutrino sum-rules [?]. Neutrino sum-rules arise, for example, in models where the neutrino mixing matrix has a certain simple form or texture at a high energy scale and the actual low-energy mixing parameters are modified by a non-diagonal charged lepton mass matrix. The simplicity of the neutrino mixing matrix is typically a result of a flavor symmetry, where the overall Lagrangian possesses an overall flavor symmetry G, which can be separated into two sub-groups G_ν and G_l for the neutrinos and charged leptons; it is the mismatch between G_ν and G_l which will yield the observed mixing pattern, see e.g. [?]. Typical candidates for G are given by discrete subgroups of SU(3) which have a three dimensional representation, e.g., A_4. In a model-building sense, these symmetries can be implemented using so-called flavon fields which undergo spontaneous symmetry breaking and it is this symmetry breaking which picks the specific realization of G, for a recent review see [?]. The idea of flavor symmetries is in stark contrast to the idea that neutrino mixing parameters are anarchic, *i.e.* random numbers with no underlying dynamics, for the most recent version of this argument, see Ref. [?]. To find out whether the patterns observed in lepton mixing correspond to an underlying symmetry is one of the prime tasks of neutrino physics. Of course, distinguishing among the many candidate underlying symmetries is also a very high priority.

In practice, flavor symmetries will lead to relations between measurable parameters, whereas anarchy will not. For example, if the neutrino mixing matrix is of tri-bi-maximal form, $|U_{e3}| = 0$ is naively expected to vanish, which is clearly in contradiction to observations. In this case, a non-diagonal charged lepton mass matrix can be used to generate the right value of $|U_{e3}|$, and, for one concrete model, the following sum-rule arises

$$\theta_{12} - \theta_{13}\cos\delta = \arcsin\frac{1}{\sqrt{3}}\,, \tag{1.11}$$

which can be tested if sufficiently precise measured values for the three parameters $\theta_{12}, \theta_{13}, \delta$ are available. Depending on the underlying symmetry of the neutrino mixing matrix different sum-rules are found. In Fig. 1-5 several examples are shown and for each case the values of θ_{13} and θ_{12} or θ_{23} are drawn many times from a Gaussian distribution where the mean values and ranges are taken from Eq. 1.8. The resulting predictions of the value of the CP phase δ are histogramed and shown as colored lines. The width of the distribution for each sum-rule arises from the finite experimental errors on θ_{12} or θ_{23} and θ_{13}. Two observations arise from this simple comparison: first, the distance of the means of the distributions is as small as 15°, and second, the width of the distributions is significant compared to their separation and a reduction of input errors is mandated. The thin lines show the results if the errors are reduced to the value given in the plot, which would be achieved by Daya Bay for $\sin^2 2\theta_{13}$, by Daya Bay II for $\sin^2\theta_{12}$, and by NOvA for $\sin^2\theta_{23}$. Assuming that the errors on θ_{12}, θ_{23} and θ_{13} are reduced to this level, the limiting factor is the natural spread between models, which is about 15°. A $3\,\sigma$ distinction between models translates into a target precision for δ of 5°. A measurement at this precision would allow to obtain valuable information on whether indeed there is an underlying symmetry behind neutrino mixing. Moreover, it is likely to also provide hints regarding which specific class of symmetries is realized. This would constitute a major breakthrough in our understanding of flavor.

For the parameter $\sin^2 2\theta_{13}$ the *status quo* is determined by the results from the reactor experiments Double Chooz [?], Daya Bay [?] and RENO [?] and their results agree well. It is expected that Double Chooz will improve its systematical error by a significant amount with the planned addition of a near detector by the end of 2013. Daya Bay started running in its full eight detector configuration only in the summer of 2012 and it is expected that a 3 year run with all detectors will eventually reach a 3% error on $\sin^2 2\theta_{13}$, compared to currently about 12.5% on this parameter. Of all beam experiments only a neutrino factory will be able to match this precision [?]. A comparison of the values of θ_{13} obtained in $\bar{\nu}_e$ disappearance at reactors with the result of ν_e and $\bar{\nu}_e$ appearance in beams will be a sensitive test of the three-flavor framework, which is particularly sensitive to non-standard matter effects.

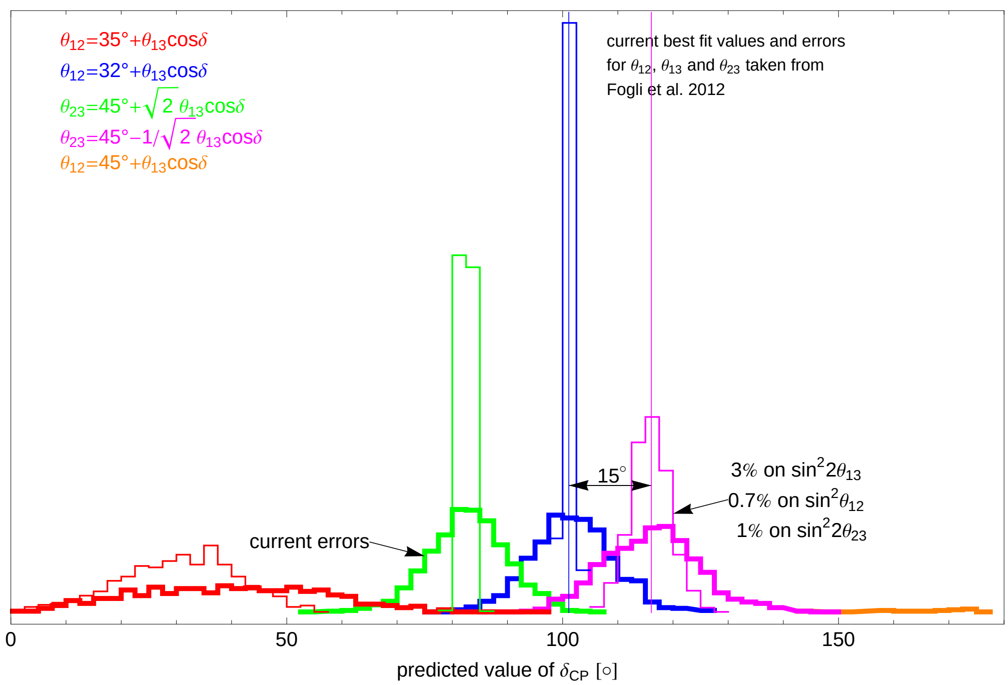


Figure 1-5. *Shown are the distributions of predicted values from δ from various sum-rule as denoted in the legend and explained in the text.*

For the atmospheric Δm^2_{31}, currently the most precise measurement comes from MINOS [**?**] with an error of 3.2% and MINOS+ [**?**] will slightly improve on this result. It is expected that both NOνA and T2K will contribute measurements with errors of $\sim 3\%$ and $\sim 4\%$, respectively. Daya Bay will provide a measurement of this parameter in $\bar{\nu}_e$ disappearance of about 4%. By increasing the size of the event sample and going to an off-axis location, CHIPS [**?**] has the potential to reduce the current error maybe be as much as a factor 2-3, which is of course subject to sufficient control of systematical errors and needs further study. Daya Bay II [**?**] ultimately may have the potential to bring the error down to below one percent. For θ_{23} two related but distinct questions arise: what is the precise value of $\sin^2 2\theta_{23}$ or how close it is to unity; and secondly, if $\sin^2 2\theta_{23} \neq 1$, is θ_{23} smaller or larger than $\pi/4$, the so-called octant of θ_{23}. An experiment can be very good at determining the value of $\sin^2 2\theta_{23}$ without obtaining any information on the octant question. The resolution of the octant question can be either achieved by comparing long-baseline data obtained at different baselines, like NOνA and T2K or by comparing a precise $\nu_\mu \to \nu_e$ long-baseline measurement with a precise determination of $\bar{\nu}_e \to \bar{\nu}_e$ oscillations from a reactor experiment like Daya Bay. Within the U.S. program, the long-baseline pieces of data can come from the NuMI beam and NOνA is well positioned, as would be potential extensions of the NuMI program in the form of extended NOνA running [**?**], GLADE [**?**] and CHIPS [**?**]. Eventually, LBNE, with its very long baseline and wide beam spectrum, will provide good sensitivity to the octant on its own. NOνA and T2K have the potential to reduce the error on $\sin^2 2\theta_{23}$ to 1-2% and most likely further improvements in beam experiments will require an improved understanding of systematics.

For the solar Δm^2_{21} the current errors are determined by KamLAND and a future improvement is necessary to measure the mass hierarchy without using matter effects as proposed by Daya Bay II. Daya Bay II is able to reduce the error to below 1%. The solar mixing parameter $\sin^2\theta_{12}$ is most accurately measured by SNO and there are basically two independent ways to further improved this measurement: One is to do a precision measurement of the solar pp-neutrino flux, since this flux can be predicted quite precisely from the solar luminosity and the $\nu - e$ scattering cross section is determined by the Standard Model, an error of 1% maybe achievable. The experimental challenge is the required very low threshold and associated low backgrounds in a large detector. The other method relies on the observation of $\bar{\nu}_e$ disappearance at a distance of about 60 km as proposed in Daya Bay II, with the potential to bring this error to below 1%. The value of θ_{12} and its associated error play an important role for sum-rules, as explained previously, but also for neutrinoless double β-decay.

In the remainder of this section, we address in more detail the two remaining experimental neutrino oscillation challenges related to "completing" the three-flavor picture, assuming it is the whole story: the determination of the neutrino mass hierarchy, and the hunt for CP-invariance violation in the neutrino sector. As will be discussed in some detail, the two issues are often, for all practical purposes, entwined.

1.4.1 Towards the Determination of the Neutrino Mass Hierarchy

Following the recent precise measurement of θ_{13} by reactor experiments one of the critical questions in neutrino physics is: What is the neutrino mass hierarchy, i.e. what is the sign of Δm^2_{31}? The hierarchy of neutrino mass states is not known and may hold the key to understanding the nature of neutrinos and their masses in the new Standard Model. The uncertainty in the sign of Δm^2_{31} leads to an uncertainty about the neutrino mass scheme allowing for two possible hierarchies: the normal hierarchy given by $m_3 \gg m_2 \gg m_1$ or the inverted hierarchy with $m_2\, m_1 \gg m_3$. We do not know which neutrino state is lightest or its absolute mass.

Measurement of mass hierarchy is key to understanding of neutrino mass, mass-generation mechanisms, and the pattern of neutrino mixing. Determination of the mass hierarchy will also provide important input for interpretation of next-generation neutrinoless double beta decay ($0\nu\beta\beta$) experiments and to the search for leptonic CP violation. It will help in the precision determination of neutrino oscillation parameters from accelerator experiments and knowing the mass ordering will allow us to get better sensitivity to CP violation. For astrophysical events such as supernovae and observations in cosmology, the ordering of neutrino mass states can no longer be neglected. An incorrect assumption about neutrino mass hierarchies can cause bias on cosmological parameters. An unambiguous determination of the mass hierarchy provides important understanding of the fundamental nature of neutrinos with profound impact in the next decade and beyond

The large matter effects implied by the recently discovered value of θ_{13} has opened the possibility of determining the mass hierarchy through a variety of different experiments and observations. This includes accelerator-based neutrino oscillation experiments, atmospheric neutrino detectors, as well as reactor antineutrino experiments, and observations of astrophysical neutrinos from supernovae, as well as cosmology. A broad suite of experiments has been proposed to study the mass hierarchy using these possibilities and R&D is underway to address the viability of these options. It is possible that one or more of these experiments will be able to make an unambiguous determination of the mass hierarchy in the next decade. More likely, we will obtain a suite of results with indications that may point to the ordering of the neutrino mass eigenstates in a joint analysis. Now that we know the size of θ_{13}, a measurement of the neutrino mass hierarchy is within reach and may well be one of the next big milestones in neutrino physics.

1.4.1.1 Mass Hierarchy from Oscillations and Other Observables

The experimental study of neutrino mass hierarchy makes use of three effects: First, the matter effects in accelerator-based, atmospheric, or SN neutrino studies. Second, subdominant oscillations in neutrino oscillations in medium-baseline reactor experiments, and third the properties of neutrino mass in neutrino less double decay experiments combined with direct neutrino mass studies or data from cosmology.

The signature of the neutrino mass hierarchy manifests itself in the oscillation signature of the three neutrino mass states and in their interactions matter. The large difference in the neutrino mass splitting often allows the simplification of 3-neutrino oscillations into an approximate effective 2-neutrino oscillation. In many experimental situations the neutrino oscillation probabilities can be approximated for 2 neutrinos, and in this case there are no CP-violating effects. In the solar regime with large L/E and $\Delta m^2_{31} L/E \gg 1$ the oscillation is driven by θ_{12} and oscillations due to the atmospheric mass differences get washed out. Indications for non-zero θ_{13} only become apparent in sub-dominant effects. In contrast, in the atmospheric regime with small L/E and $\Delta m^2_{21} L/E \ll 1$, the oscillation is driven by θ_{23}, the near maximal conversion between ν_μ and ν_τ. For large L/E, the Δm_{21} term dominates and can be measured precisely as shown by KamLAND. In this regime the θ_{23} oscillation becomes a subdominant effect. But in principle and with sufficient energy resolution in the experiments, the interplay of the subdominant oscillation terms with Δm_{31} and Δm_{32} can provide sensitivity to the mass hierarchy. This is the goal of future medium-baseline reactor experiments.

Another experimental signature for the neutrino mass hierarchy comes from the matter effect, the additional interaction of electron neutrinos with electrons in matter. The large value of θ_{13}, along with the neutrino versus anti-neutrino dependent matter resonance effect opens up the study of oscillation driven ν_e appearance effects. Matter-enhanced neutrino oscillations as described in the MSW effect, have been observed for solar neutrinos, and hence the sign of Δm^2_{21} is known. These matter effects may also be within reach of atmospheric neutrino detectors which would determine the sign of Δm^2_{31}. For atmospheric neutrinos the highest sensitivity to the mass hierarchy is obtained for neutrinos of 5-10 GeV which traverse the Earth at zenith angles of 30-60°. Neutrino oscillations in long-baseline accelerator experiments include the combination of oscillation and matter effects and show the interference between the solar and neutrino oscillation terms in the oscillation probability. The interference contains the dependence on the CP-violating phase δ and also depends on the mass hierarchy. For vanishing θ_{13} the determination of the mass hierarchy through neutrino oscillations would have been impossible. The matter effects in the atmospheric sector grow with the second power of θ_{13} and linearly in the interference term which increases the effect at lower energies and short baselines. As a result, a suite of experimental proposals have been put forward based on precision studies of reactor antineutrino, atmospheric neutrinos, and accelerator-based neutrinos.

Astrophysics and cosmology provide complete different approaches to the determination of the neutrino mass hierarchy. Core collapse supernovae (SN) from massive stars are an abundant source of neutrinos of all flavors: see Sec. 1.9.2.1. There are multiple possible signatures sensitive to mass hierarchy in the supernova neutrino flux. During neutrino emission from the SN core the MSW effects are encountered twice at high and low density, and the resulting flavor conversion depends on the neutrino mass hierarchy in addition to the star's density, neutrino energy, and the oscillation parameters. In addition, shock waves in the SN envelope and Earth matter effects can impact the observed neutrino spectra. Shock waves change the adiabatic to non-adiabatic conversion and multiple MSW effects take place. They occur either in the ν_e or $\overline{\nu_e}$ channel and depend on the mass hierarchy. Turbulences have similar effects as shock waves. In addition, neutrino conversion can take place near the neutrino sphere due to ν-ν interactions. The conversion probability is energy dependent and may introduce a spectral split. Model-dependent effects in the emitted SN spectrum will have to considered in the use of SN data for a mass hierarchy determination.

Cosmological observations provide additional information on neutrinos, in particular the total sum of neutrino masses. The relic neutrino background is similar to that of CMB photons; they decouple at 1 MeV and then freeze out with expansion. The mean energy of the cosmic neutrino background is related to their temperature and cosmic neutrinos contribute to the total matter budget of the Universe. Neutrino also impact the observed CMB power spectra through a non-relativistic transition before the photon decoupling. In addition, neutrinos alter the matter-radiation inequality, in particular the size of the sound horizon at decoupling. The free-streaming properties of the neutrino also leave an imprint on the large scale structure power spectrum as neutrino speed avoids clustering. Together these observations and models can provide impressive constraints on the sum of the neutrino masses and some may argue that neutrino masses will be inferred from cosmology in the next decade. If the sum of the neutrino masses is measured to be $\sum m_\nu \leq 0.1$ eV the inverted mass hierarchy would automatically be excluded.

1.4.1.2 Experimental Approaches

Accelerator Experiments Ongoing and future accelerator experiments are a key element in a program to determine the neutrino mass hierarchy. Very intense beams of muon neutrinos from pion sources can be used to search for electron neutrino appearance. For intermediate and long baselines the appearance probability will depend on the ordering of the neutrino mass states. The upcoming NOvA experiment together with T2K will have a chance of determining the neutrino mass hierarchy with accelerator neutrinos for a range of oscillation parameters. In the long-term, the long-baseline neutrino oscillation experiment (LBNE) or experiments at neutrino factories will allow the definitive measurement of the neutrino mass hierarchy. See Figure 1-6. The CHIPS and GLADE seek to exploit the NuMI beam from FNAL with new detectors at baselines similar to MINOS and NOvA. The experimental advantages of LBNE over current experiments such as NOvA and T2K include an optimum baseline from the neutrino source to the detector, a large and highly capable far detector, a high-power, broadband, sign-selected muon neutrino beam, an a capable near neutrino detector. If placed underground, the LBNE far detector may even allow the possibility of atmospheric neutrino studies and oscillation measurements through a channel with different systematics than the accelerator-based experiments. Optimization of the LBNE baseline to determine the mass hierarchy with no ambiguities depends only on the known oscillation parameters. To achieve mass hierarchy sensitivity over all phase space requires a baseline >1000 km.

Reactor Experiments - The success of recent reactor experiments in the measurement of θ_{13} at baselines of $\sim$1 km has resulted in proposals for the precision study of neutrino oscillation at medium baselines of 50-60 km. A high-precision, high statistics reactor experiment at 60 km may be able to determine the mass hierarchy from the difference in the oscillation effects from Δm^2_{31} and Δm^2_{32}. See Figure 1-7. Such a measurement is challenging due to the finite detector resolution, the absolute energy scale calibration, as well as degeneracies caused by current experimental uncertainty of Δm^2_{32}. Two experiments are currently proposed to make this measurement: Daya Bay II in China and RENO-50 in South Korea, although other locations may be suitable. The current design of RENO-50 includes a 5 kton liquid scintillator detector 50km from a 17 GWth power plant. Daya Bay II proposes a 20 kton liquid scintillator detector 700 m underground and 60 km from two nuclear power plants with 40 GWth power.

Atmospheric Neutrino Experiments – Atmospheric neutrino experiments have played a historic role in neutrino physics. From the first observation of the atmospheric neutrino anomaly to the discovery of neutrino oscillations in Super-Kamiokande in 1998 precision studies of neutrinos produced in the Earth's atmosphere have been critical to our understanding of neutrino oscillations. Atmospheric neutrinos remain an important probe of neutrino oscillations and the large statistics that can be collected by large Cherenkov detectors at the Mton-scale such as Hyper-K, PINGU, and ORCA will offer an an unprecedented opportunity to study them in detail. Atmospheric neutrinos exist in both neutrino and anti-neutrino varieties in both

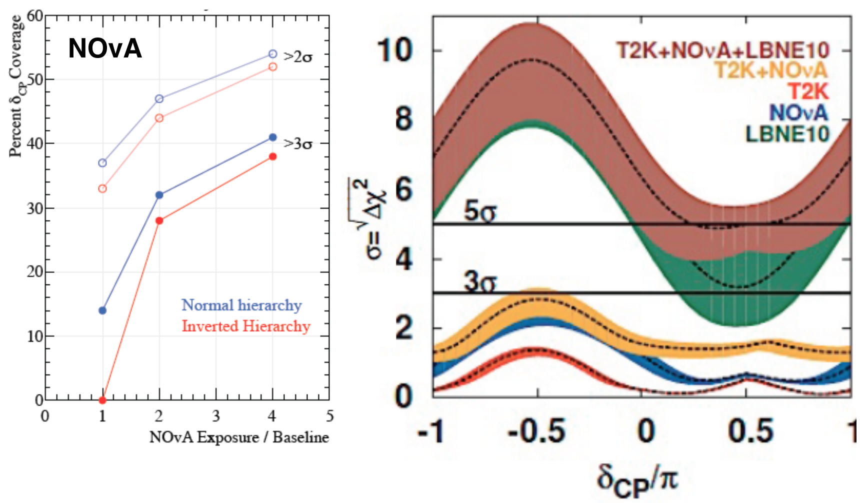


Figure 1-6. *Left: Percent of δ_{CP} values for which NOvA can resolve the neutrino mass hierarchy at 2 and 3 σ C.L. NOvA is in construction and has started data taking with a partial detector configuration. Right: Mass hierarchy sensitivity of LBNE10, NOvA, and T2K and combinations thereof. T2K is operational and taking data. NOvA is in the commissioning phase and will finish construction in 2014. LBNE10 is in preliminary design and R&D and preparing for Critical Decision 2. Figures from [**?**, **?**].*

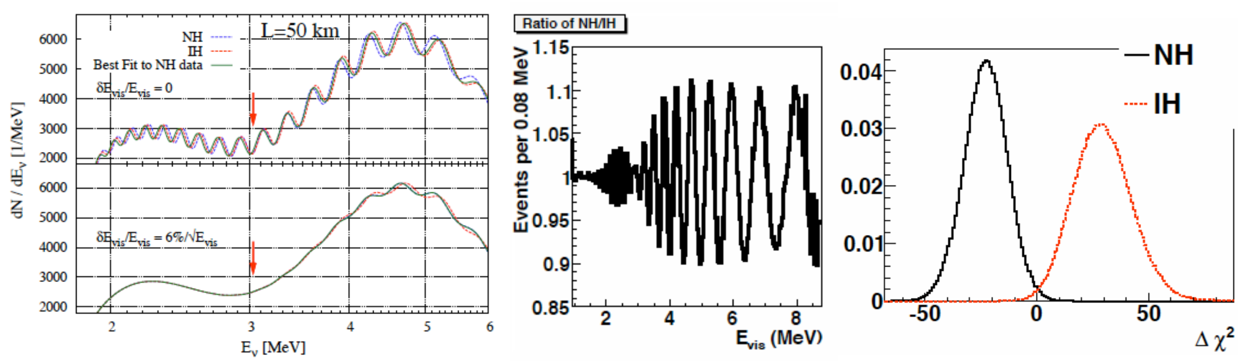


Figure 1-7. *Left: Energy distribution of reactor antineutrinos with baseline length of 50 km. The solid line shows the best fit of IH assumption to the NH data. The red arrow points out the energy at which the difference due to the mass hierarchy vanishes. The lower panel shows the effect of 6% energy resolution. Figure from [**?**]. Middle: Ratio of reactor antineutrino spectra for NH and IH case for the ideal energy spectrum without fluctuation and fixed Δm^2_{31} . Statistical fluctuations, the unknown true value of Δm^2_{31}, as well as experimental effects such as energy scale uncertainty will degrade the observable effect. Right: The $\Delta\chi^2$ spectrum from Monte Carlo simulation. The probability of the mass hierarchy being NH is calculated as $P_{NH}/(P_{NH}+P_{IH})$ and found to be 98.9% for 100kT-year exposure. Figures from [**?**].*

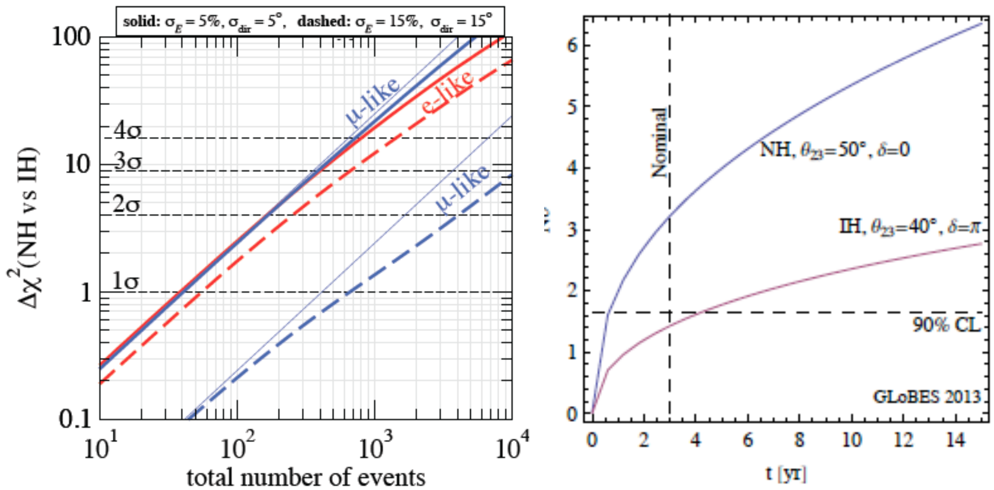


Figure 1-8. *Atmospheric neutrino oscillations can determine the mass ordering with large number of events and good energy and angular resolution. Left: Left: $\Delta\chi^2$ between NH and IH as a function of total number of events [?]. Right: Discovery potential of the proposed PINGU atmospheric neutrino experiment to mass hierarchy as a function of time for two extreme cases of the true parameter values. The vertical dashed line indicates a nominal experimental configuration described in [?]. A 3σ discovery is conceivable with 3 years of data taking. Figure from [?].*

muon and electron flavors. Up to 10^6 events are expected to be collected in a 10-year period in half megaton detectors such as Hyper-K. There are two experimental approaches to the study of the mass hierarchy with atmospheric neutrinos. One approach is based on charge discrimination and distinguishes between neutrinos and antineutrinos. Large magnetized calorimeters such as INO [?] with good energy and angular resolution and thresholds of 1-2 GeV are an example of this type of detector. The second approach uses water Cherenkov detectors and makes use of the different cross-sections and different ν and $\overline{\nu}$ fluxes. Examples of future water Cherenkov detectors include Hyper-K [?], a larger version of the successful water-based Super-K detector, ORCA, an extension of ANTARES in the Mediterranean Sea [?], and PINGU, an upgrade of the IceCube Deep Core detector at the South Pole [?]. Atmospheric neutrino measurements are also possible in large liquid argon TPCs such as that being planned for LBNE. Key to the measurement of the mass hierarchy with these experiments will be a large statistical sample collected in a large fiducial volume, good energy and angular resolution for the study of the L/E oscillation effects and discrimination of backgrounds. See Figures 1-8, 1-9, and 1-10.

Supernova Studies – A suite of neutrino observatories is currently operational worldwide with a variety of target materials including water or ice (Super-K, IceCube), liquid scintillator (KamLAND, Borexino, Daya Bay, MiniBoone, LVD), and lead (HALO). They offer a suite of detection channels through the scattering of $\overline{\nu_e}$ with protons, the ν_e scattering with nuclei and ν_x interactions with electrons and protons. Together they have the ability to measure the SN flux at different thresholds and different flavor sensitivities. The observation of SN will offer a rich physics opportunity with discovery potential if we are lucky enough to observe during the lifetime of these experiments.

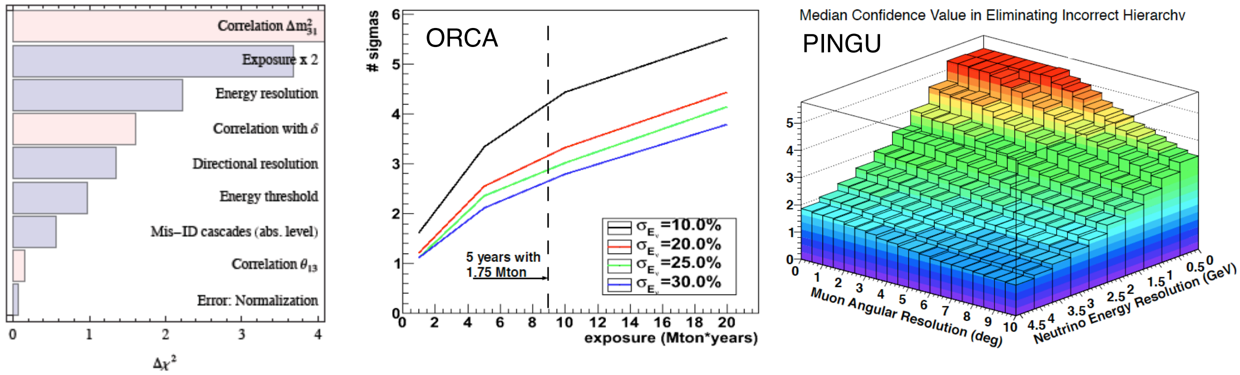


Figure 1-9. *Left: Impact of experimental and systematic uncertainties on the determination of the mass hierarchy with atmospheric neutrino experiment such as PINGU and ORCA. The impact is given in form of $\Delta\chi^2$ for normal hierarchy and $\delta = 0$ on the default systematics described in [?]. The blue bars indicate experimental systematics. The exposure, energy scale, and directional resolution are most important for the experiment under consideration. Figure from [?]. Right: Sensitivity of the ORCA and PINGU proposals to mass hierarchy as a function of events, angular, and energy resolution. Experimental sensitivities are preliminary. Figure from [?, ?]*

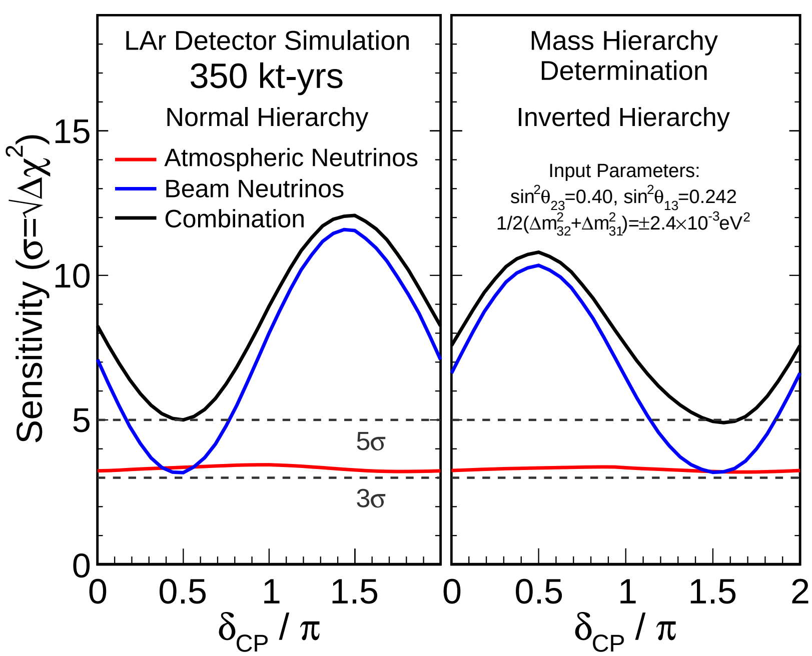


Figure 1-10. *Mass hierarchy determination possible with atmospheric neutrinos in a 35 kton-year exposure of an underground liquid argon TPC in LBNE shown as a function of possible δ_{CP} values for both normal (left) and inverted (right) hierarchies. Atmospheric neutrino information can be combined with beam information in the same detector to improve overall sensitivity. Plot courtesy of A. Blake.*

1.4.1.3 Experimental Status and Opportunities

The measurement of large θ_{13} has opened a broad range of possibilities for the determination of the neutrino mass hierarchy. Several experiments with complementary approaches have been proposed that will allow us to determine the neutrino mass hierarchy in oscillation experiments using neutrinos from accelerators, reactors, or the atmosphere. NOvA is the only funded oscillation experiment under way to start an experimental investigation of the neutrino mass hierarchy in a range of the allowed parameter space. T2K is taking data but only has a weak dependence due its short baseline. For some of the recent proposals under consideration sometimes significant R&D and design work is still required. A dedicated experiment to measure the neutrino mass hierarchy with atmospheric or reactor neutrinos may be feasible by 2018. After 2022, the planned LBNE experiment will be able to determine the neutrino mass hierarchy for the entire range of CP values. In the mean time double beta decay and direct neutrino mass experiments combined with data from cosmology may also tell us about the hierarchy if $\sum m_\nu$ is measured to be less than 0.1 eV. A supernova event detected in one or several of the existing large neutrino observatories would enable a rich physics program and may allow the determination of the ordering of the neutrino mass states. Astrophysics and uncertainties in the supernova models make this challenging. Table 1-3 summarizes the status of the ongoing and proposed experiments.

Category	Experiment	Status	Start Date	US Participation/ Leadership	Osc params	References
accelerator	T2K	data taking	ongoing	yes/no	MH/CP/oct.	[]
accelerator	T2HK	data taking	ongoing	yes/no	MH/CP/oct.	[]
accelerator	NOνA	commissioning	2014	yes/yes	MH/CP/oct.	[]
accelerator	GLADE	R&D	2018?	yes/yes	MH/CP/oct.	[]
accelerator	CHIPS	R&D	2018?	yes/yes	MH/CP/oct.	[]
accelerator	LBNE	design/ R&D	2022	yes/yes	MH/CP/oct.	[?]
accelerator	DAEδALUS	design/ R&D	2022	yes/yes	CP	[?]
reactor	Daya Bay II	design/R&D	2018	undecided/no	MH	[?]
reactor	RENO-50	design/R&D	2018		MH	[]
atmospheric	Hyper-K	design/R&D	2020	yes/no	MH/CP/oct.	[?]
atmospheric	INO	design/ R&D	2020		MH/oct.	[]
atmospheric	PINGU	design/ R&D	2018	yes/yes	MH	[?]
atmospheric	ORCA	design/R&D	2018		MH	[?]
supernova	existing	N/A	N/A	various	MH	[]

Table 1-3. *Ongoing and proposed oscillation experiments for the measurement of neutrino oscillation parameters.*

From the early days of neutrino physics the US has hosted and been a leader in several historic neutrino experiments. The first solar neutrino experiment, studies of the atmospheric neutrino anomaly, and neutrino mass experiments were performed in the US. In recent years US scientists have played major roles in experiments overseas including Super-K, SNO, KamLAND, Daya Bay and others. In addition, the US has pursued a successful domestic neutrino oscillation program with MINOS, MiniBooNE, and others. With NOvA followed by LBNE, the US will lead the experimental determination of the neutrino mass hierarchy with accelerator neutrinos for the next decade and beyond. Reactor and atmospheric neutrinos may offer the opportunity for alternative, complementary measurements with possibly earlier results. Ongoing R&D will establish the viability of these proposals. US universities and national laboratories have been leaders in the study of reactor neutrinos and have pioneered the study of atmospheric neutrino with the largest particle physics detector ever built, IceCube. The quest for the neutrino mass hierarchy offers the opportunity for US leadership and participation with discovery potential in several international experiments.

1.4.2 Towards the Determination of CP Violation in Neutrinos

The standard approach to measuring CP violation in neutrinos is to use long-baseline beams of both neutrinos and neutrinos. As for the mass hierarchy determination, nature provides beams of atmospheric neutrinos and antineutrinos free of charge, over a wide range of energies and baselines– the catch is that one has no control over their distribution and so one must measure their properties precisely, and/or gather immense statistics in order to extract information on CP violation from these sources. Alternate approaches include using well-controlled, well-understood accelerator-based beams of neutrinos or lower-energy neutrinos from pion decay-at-rest sources. Here, we will discuss the CP reach of all three options: accelerator-based long-baseline neutrinos, atmospheric neutrinos, and pion decay-at-rest sources.

1.4.2.1 CP Violation with Accelerator-Based Long-Baseline Neutrinos

Current and next-generation accelerator-based experiments plan to exploit the CP-violating signal that manifests itself as an energy-dependent appearance of electron neutrinos observed a long distance away from a well-prepared source of muon neutrinos. Difference in the effects seen for both neutrinos and antineutrinos futher enables a definitive determination of CP violation. For baselines long enough that matter effects are important, the signal is also affected by the mass hierarchy (see Section 1.4.1). The CP asymmetry arising from non-zero/non-π values of δ_{CP} is largest at the secondary oscillation node and is constant as a function of baseline whereas the asymmetry due to matter effects dominates at the first oscillation node and increases with longer baselines. Therefore, an experiment with a wide-band beam of neutrinos and antineutrinos that can cover at least two oscillation nodes over a long enough baseline ($>$ 1000 km) can unambiguously determine both the mass hierarchy and the CP phase simultaneously. This is the philosphy behind the Long-Baseline Neutrino Experiment (LBNE). Additionally, the study of $\nu_\mu \to \nu_e$ oscillations can help determine the θ_{23} quadrant since the oscillation probability is also proportional to $\sin^2\theta_{23}$ and $\cos^2\theta_{23}$.

Figure 1-11 shows examples of observed spectra for a 1300 km baseline and a beam of a few GeV (the LBNE/Project X configuration with a LAr TPC far detector) for ν_e and $\bar{\nu}_e$ appearance. Different values of δ_{CP} correspond to different spectral shapes for neutrinos versus antineutrinos; also, the ν_e signal is larger in neutrinos for the normal mass hierarchy and in antineutrinos for the inverted hierarchy. Good event reconstruction and rejection of background are critical for this measurement. In the case of LBNE, a LAr TPC was chosen as the far detector technology given its excellent 3D position resolution and superior particle identification in large volumes. In addition to detailed event topologies and measurements of particle kinematics, such detectors can also unambiguously distinguish electrons from photons over a wide range of energies, an important asset in the precision measurement of CP violating effects in $\nu_\mu \to \nu_e$ oscillations.

Figure 1-12 illustrates the significance with which measurements of CP violation and the unknown CP phase can be made with a staged long-baseline neutrino program in LBNE [?]. Ultimately, a 5σ determination of CP violation and a $\leq 10^\circ$ measurement of the CP violating phase are possible with such an experimental program.

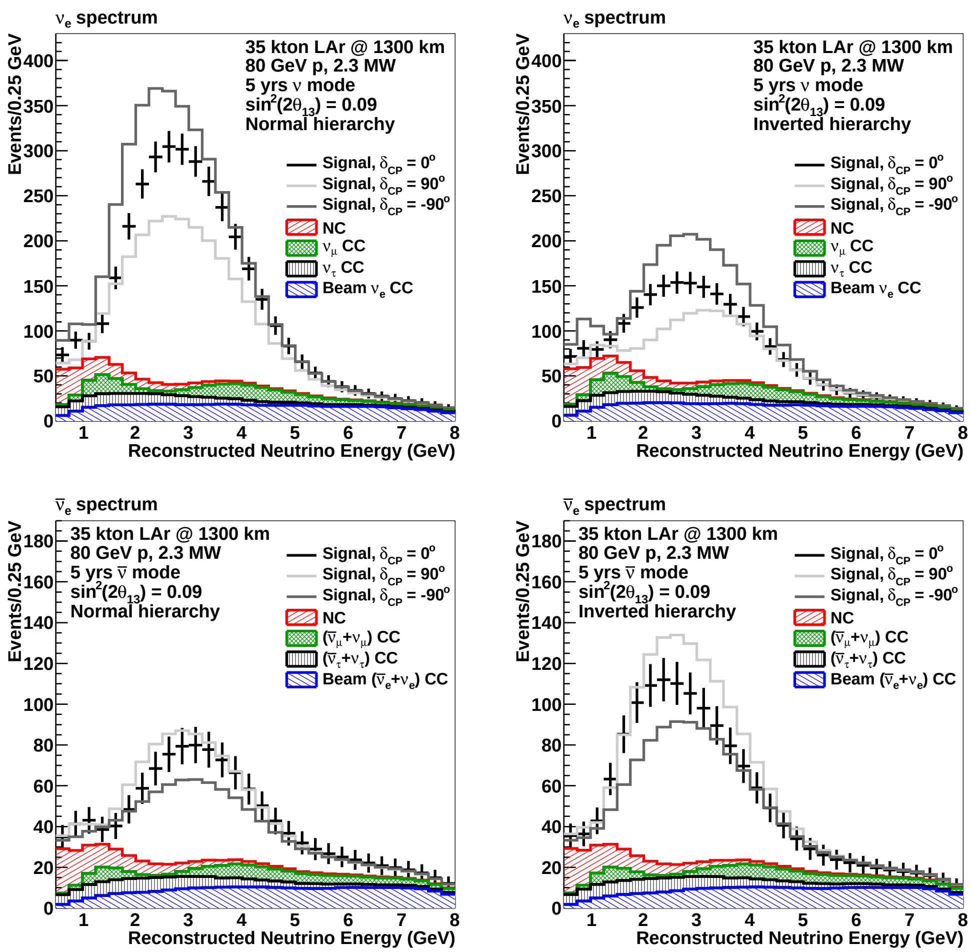


Figure 1-11. *The expected appearance of ν_e (top) and $\bar{\nu}_e$ (bottom) signals for the possible mass orderings (left: normal hierarchy, right: inverted hierarchy) and varying values of CP δ for the example of LBNE/Project X.*

LBNE plays a central role in the future U.S. program, and while being the most advanced of all the proposals to measure CP violation in the neutrino sector, there is a large number of alternative proposals in the U.S. and abroad. In this short document, we will not be able to provide an in-depth comparison of the scientific merit of each of these proposals. Nonetheless, we can give an impression of how their performance for specific measurements might look like. The most challenging measurement within the framework of oscillation of three active neutrinos for long-baeline experiment is the search for leptonic CP violation and a precise measurement of the associated CP phase, δ_{CP}. Therefore, apart from the value of a determination of δ_{CP}, as outlined in Sec. 1.4, the ability to measure the CP phase with precision is a reasonable proxy for the overall potential to have a major scientific impact.

The results of this comparison are shown in Fig. 1-14 using the methods and common systematics implementation including near detectors as in Ref. [**?**]. The lines labeled 2020 and 2025 show what can be achieved by those dates using a combination of the existing experiments T2K and NOνA and Daya Bay, where the implentation of all three follows Ref. [**?**] and the NOνA description has been updated for this report [**?**]. This is the precision which can be reached without any new experiments. Furthermore, we will compare two phases of LBNE: LBNE-1 with a 10 kt detector and a 700 kW beam and LBNE-PX with a 34 kt detector and the 2.3 MW beam from Project-X; both phases do include a near detector and the other details can be found in the previous section on LBNE. Note, that the beam assumed is the nominal LBNE beam based on 120 GeV protons, if an optimized 80 GeV beam were available then the result for LBNE-1 would improve by about 5° and for LBNE-PX by about 2°.

Beyond LBNE, we compare three different superbeam experiments, the European LBNO proposal for two different exposures and the Japanes proposal to send a beam to Hyper-Kamiokande. LBNO plans to use liquid argon TPC, based on dual phase readout in contrast to LBNE, and a baseline of 2 300 km. The initial detector size will be 20 kt (labeled $\mathrm{LBNO_{EOI}}$) as descibed in detail in Ref. [**?**] and a later phase using a 100 kt detector (labeled $\mathrm{LBNO_{100}}$); the beam power will be aorund 700 kW derived from the CERN SPS. The T2HK setup [**?**] in Japan will use a 560 kt water Cerenkov detector and a 1.66 MW beam, however the running time will be only 5 years in total, so even if the beam power ultimately were reduced as consequence of the tsunami damage, in 10 years of running time, like most experiments in Fig. 1-14, the same overall exposure would be reached.

Finally, we also show the results obtained from a neutrino factory (NF) – in a neutrino factory an intense beam of muons is put in a storage ring with long straight sections and a neutrino beam conssisting of equal numbers of ν_μ and $\bar{\nu}_e$ results. The current standard design of a neutrino factory will produce 10^{21} useful muon decays (summed over both stored μ^- and μ^+) per 10^7 s at a muon energy of 10 GeV aimed a 100 kt magnetized iron detector (MINOS-like) at a distance of 2 000 km [**?**]. This facility requires a 4 MW proton beam at around 8 GeV, muon phase space cooling and subsequent muon acceleration. This considerable technical challenge should be contrasted with the resulting adavantages: a neutrino beam with known flux, better than 1%, beam spectrum and flavor composition with an easy to identify final state in the far detector. NF offer a unique level of systematics control paired with very high intensity beams, therefore they are considered the ulimate tool for precision neutrino physics, see, e.g., Ref. [**?**]. The NF is the only known method to achieve a precision for the CP phase in the lepton sector comparable to the one in the quark sector.

Several new proposals have been submitted in the form of white papers, notably a series of ideas how to use the existing Main Injector neutrino beam line (NuMI) by adding new detectors. GLADE [**?**] proposes to add 5-10 kt of a liquid argon TPC in the NOνA far detector hall at a baseline of 810 km. CHIPS [**?**] proposes to build water Cerenkov detectors in shallow, flooded mine pits, which could provide pontentially large fiducial masses in the range of 100 kt. According to the proponents, in terms of physics reach, this would be equivalent to about 20 kt of liquid argon TPC. GLADE and CHIPS, together with NOνA, T2K, Daya Bay and potential beam power upgrades of the NuMI beamline to about 1 MW have a CP measurement potential similar or maybe even exceeding phase 1 of LBNE on a comparable time scale. Clearly, for CHIPS considerable R&D is still required and thus, the cost is not well understood. For both GLADE and CHIPS the longterm persepective to improve CP precision to 15° or better for a large fraction of the phase space is unclear and in particular, systematic effects may limit these approaches well before that. A staged approach to a neutrino factory is proposed [?], where an initial stage called the low-luminosity low-energy neutrino factory is built on the basis of existing accelerator technology and Project X phase 2. In this facility, which does not require muon cooling and which starts with a target power of 1 MW, 10^{20} useful muon decays per polarity and year can be obtained. The muon energy is chosen to be 5 GeV as to match the baseline of 1 300 km. In combination, this allows to target the LBNE phase 1 detector, maybe with the addition of a magnetic field. This approach would allow for a step-wise development from νSTORM, see Sec. 1.8, via the low-luminosity low-energy neutrino factory to a full neutrino factory, and if desired, to a multi-TeV muon collider. This phased muon-based program is well aligned with the development of Project X.

In summary, measuring the leptonic CP phase to a very high level of precision is feasible in long-baseline experiments thanks to the measured large value of θ_{13}. To do so will require very high beam intensities in excess of one megawatt and detectors in the 100 kt range paired with runtimes of the order of a decade while at same time maintaining percent level or better systematics – this is true independently of the specifics of the chosen technology or proposal.

1.4.2.2 CP Violation with Atmospheric Neutrinos

As noted above, neutrinos and antineutrinos from the atmosphere come with a range of baselines and energies and in principle similar CP-violating observables are accessible as for beams, for detectors with sufficient statistics and resolution. Water Cherenkov detectors have relatively low resolution in energy and direction, and have difficulty selecting neutrinos from antineutrinos, although some information is to be had via selection of special samples [?] and using statistical differences in kinematic distributions from ν and $\bar{\nu}$; the advantage of water Cherenkov detectors is the potentially vast statistics. Figure 1-15 shows example allowed regions for 10 years of Hyper-K running. Large long-string ice and water-based detectors, while sensitive to hierarchy if systematics can be reduced, lack resolution for CP studies. LArTPC detectors, in contrast, should have significantly improved resolution on both neutrino energy and direction, and even in the absence of a magnetic field can achieve better ν vs $\bar{\nu}$ tagging than water Cherenkov. Figure 1-16 shows an example sensitivity plot for a liquid argon detector like LBNE. Atmospheric neutrino information can be combined with beam information in the same or different detectors to improve overall sensitivity.

1.4.2.3 CP Violation with Pion Decay-at-Rest Sources

A different approach for measuring CP violation is DAEδALUS [?, ?, ?]. The idea is to use electron antineutrinos produced by cyclotron stopped-pion decay at rest (DAR) neutrino sources, and to vary the baseline by having sources at different distances from a detector site. For DAR sources, the neutrino energy is a few tens of MeV. For baselines ranging from 1 to 20 km, both L and E are smaller than for the conventional long baseline beam approach, and the ratio of L/E is similar. Matter effects are negligible at short baseline. This means that the CP-violating signal is clean; however there is a degeneracy in oscillation probability for the two mass hierarchies. This degeneracy can be broken by independent measurement of the hierarchy.

The program requires free proton targets, hence either water or scintillator detectors.The original case was developed for a 300 kt Gd-doped water detector at Homestake, in coordination with LBNE [?]. Possibilities currently being explored for the detector include LENA [?] or Super-K/Hyper-K [?].

Figure 1-17 shows the projected CP sensitivity.

The DAEδALUS collaboration proposes a phased approach [**?**, **?**], with early phases involving IsoDAR [**?**] (see Section 1.8.1.3) with sterile neutrino sensitivity. The program offers also connections to applied cyclotron research [**?**] (see Section 1.10.5.2).

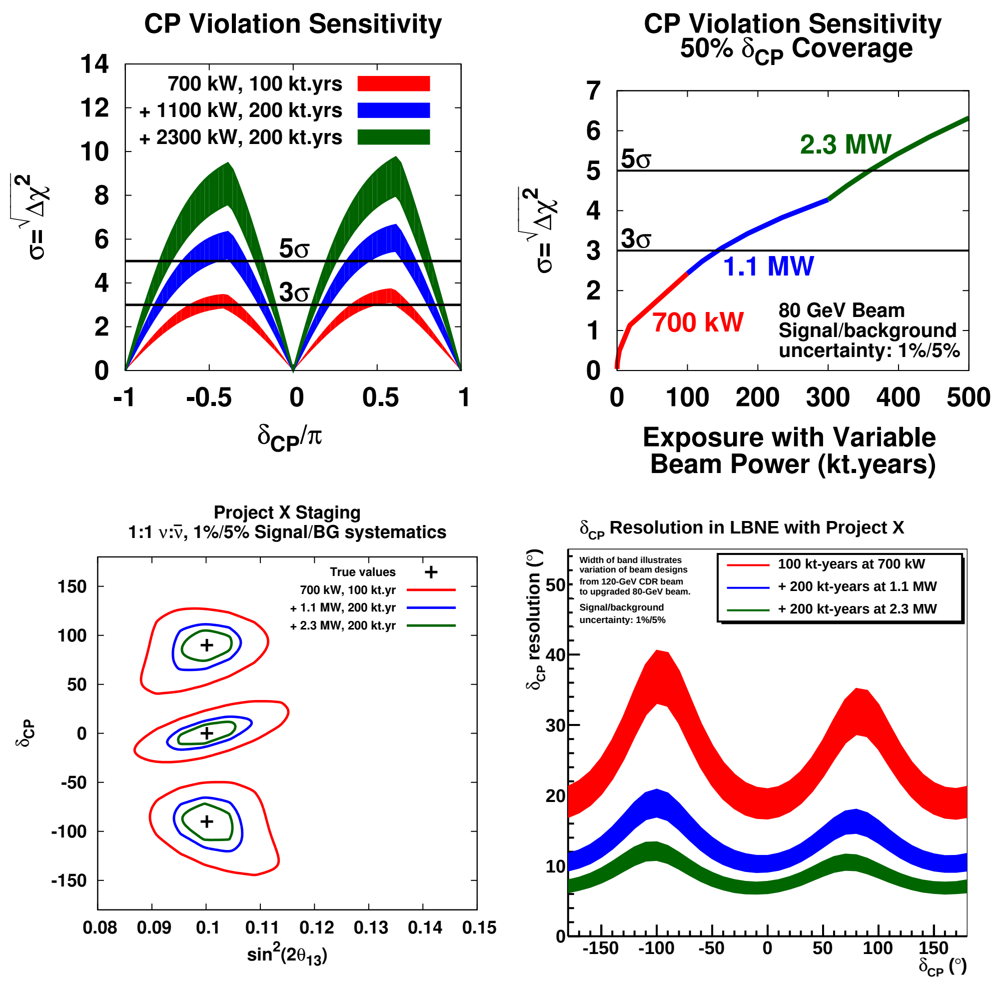


Figure 1-12. *CP violation sensitivity as a function of δ_{CP} (top left) and exposure for 50% coverage of the full δ_{CP} range (top right). Also shown are the projected precision on the measurement of δ_{CP} for various true points in the δ_{CP}-$\sin^2 2\theta_{13}$ plane (bottom left) and as a function of δ_{CP} (bottom right). All plots show the increasing precision possible in a staged long-baseline neutrino program in LBNE starting from nominal 700kW running (red), through 1.1 MW using Project X Stage 1 (blue), to 2.3 MW with Project X Stage 2 (green).*

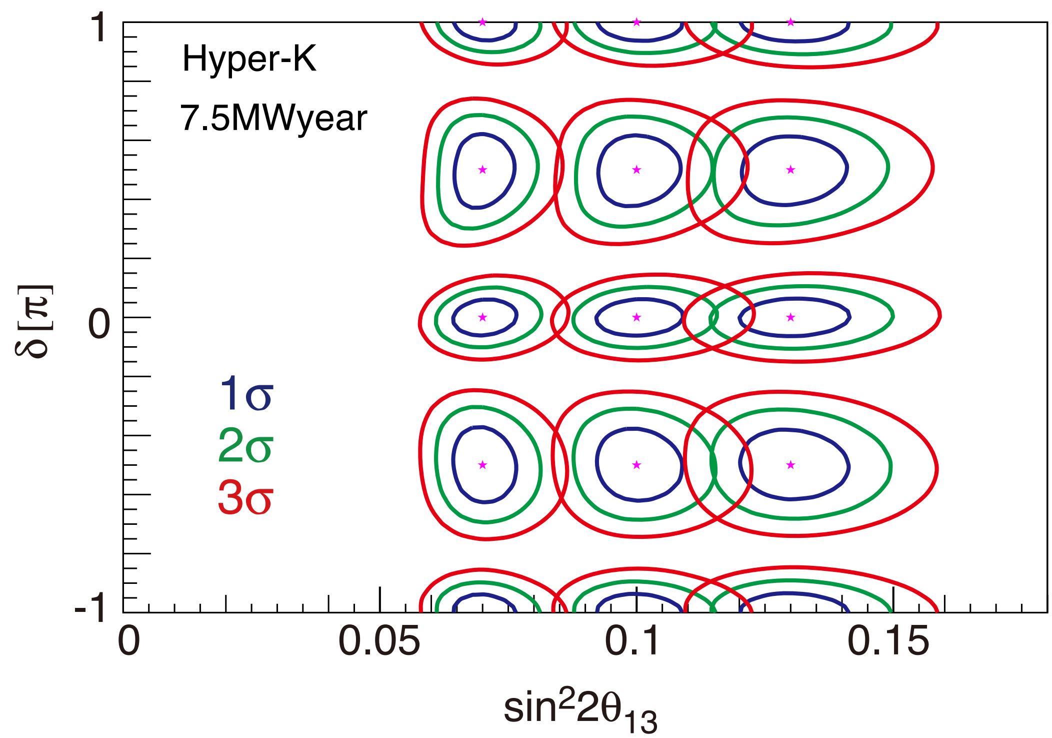


Figure 1-13. *Example allowed regions for various true points in the δ_{CP}-$\sin^2(2\theta_{13})$ plane, for different Hyper-K exposures [**?**].*

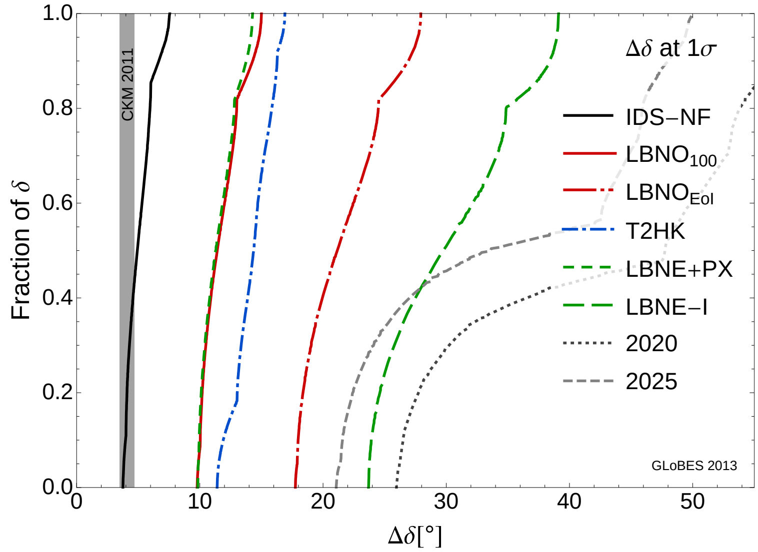


Figure 1-14. *Projected precision for a CP measurement. Shown is the fraction of all possible true values of δ_{CP} as a function of the 1σ error in the measurement of δ_{CP}. A CP fraction of 1 implies that this precision will be reached for all possible CP phases, wheras a CP fraction of 0 means that there is only one value of δ_{CP} for which the measurement will have that precision. The various lines are for a variety of possible experiments as labeled in the legend and explained in the text. The vertical gray shaded area, labeled "CKM 2011", indicates the current errors on the CP phase in the CKM matrix. This calculation includes near detectors and assumes consistent flux and cross section uncertainties across different setups. Plot courtesy of P. Coloma.*

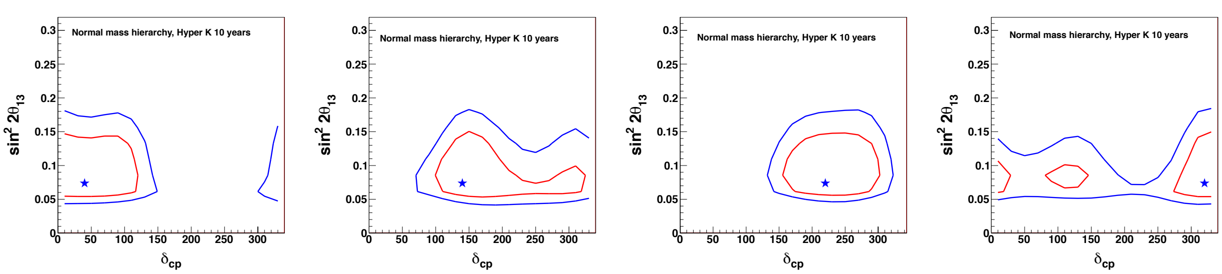


Figure 1-15. *Expected sensitivities for δ and $\sin^2 2\theta_{13}$ at 90% CL (red) and 99% CL (blue) with a livetime of 10 Hyper-K years. Stars in the contours represent the true parameters. Normal mass hierarchy is assumed. Figure from* [**?**].

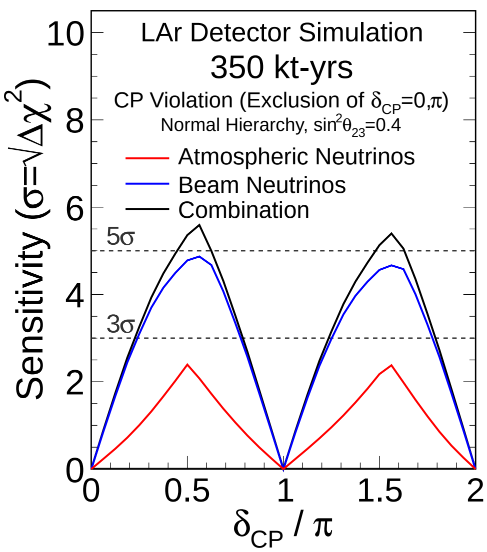


Figure 1-16. *Sensitivity to CP violation as a function of δ_{CP} for a liquid argon detector showing the results of combining information from both beam (blue) and atmospheric (red) neutrinos. Plot courtesy of A. Blake.*

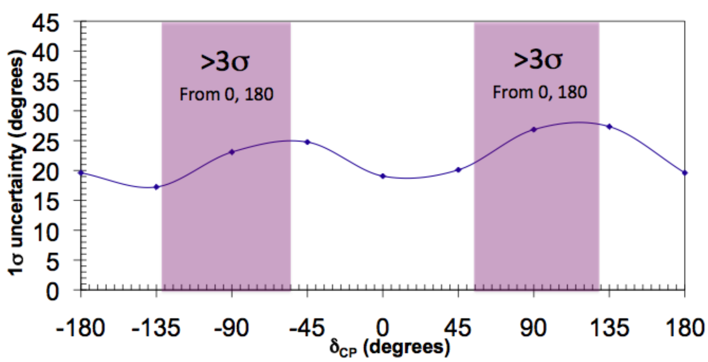


Figure 1-17. *Sensitivity of a CP search for DAEδLUS combined with LENA.*

1.5 The Nature of the Neutrino – Majorana versus Dirac

With the realization that neutrinos are massive, there is an increased interest in investigating their intrinsic properties. Understanding the neutrino mass generation mechanism, the absolute neutrino mass scale, and the neutrino mass spectrum are some of the main focuses of future neutrino experiments. Whether neutrinos are Dirac fermions (*i.e.*, exist as separate massive neutrino and antineutrino states) or Majorana fermions (neutrino and antineutrino states are equivalent) is a key experimental question, the answer to which will guide the theoretical description of neutrinos.

All observations involving leptons are consistent with their appearance and disappearance in particle anti-particle pairs. This property is expressed in the form of lepton number, L, being conserved by all fundamental forces. We know of no fundamental symmetry relating to this empirical conservation law. Neutrinoless double-beta decay, a weak nuclear decay process in which a nucleus decays to a different nucleus emitting two beta-rays and no neutrinos, violates lepton number conservation by two units and thus, if observed, requires a revision of our current understanding of particle physics. In terms of field theories, such as the Standard Model, neutrinos are assumed to be massless and there is no chirally right-handed neutrino field. The guiding principles for extending the Standard Model are the conservation of electroweak isospin and renormalizability, which do not preclude each neutrino mass eigenstate ν_i to be identical to its antiparticle $\overline{\nu}_i$, or a Majorana particle. However, L is no longer conserved if $\nu = \overline{\nu}$. Theoretical models, such as the seesaw mechanism that can explain the smallness of neutrino mass, favor this scenario. Therefore, the discovery of Majorana neutrinos would have profound theoretical implications in the formulation of a new Standard Model while yielding insights into the origin of mass itself. If neutrinos are Majorana particles, they may fit into the leptogenesis scenario for creating the baryon asymmetry, and hence ordinary matter, of the universe.

As of yet, there is no firm experimental evidence to confirm or refute this theoretical prejudice. Experimental evidence of neutrinoless double-beta ($0\nu\beta\beta$) decay would establish the Majorana nature of neutrinos. It is clear that $0\nu\beta\beta$ experiments sensitive at least to the mass scale indicated by the atmospheric neutrino oscillation results are needed.

For $0\nu\beta\beta$ decay the summed energy of the emitted electrons is mono-energetic. Observation of a sharp peak at the $\beta\beta$ endpoint would thus quantify the $0\nu\beta\beta$ decay rate, demonstrate that neutrinos are Majorana particles, indicate that lepton number is not conserved, and, paired with nuclear structure calculations, provide a measure of an effective Majorana mass, $\langle m_{\beta\beta}\rangle$. There is consensus within the neutrino physics community that such a decay peak would have to be observed for at least two different decaying isotopes at two different energies to make a credible claim for $0\nu\beta\beta$ decay.

In more detail, the observed half-life can be related to an effective Majorana mass according to $(T_{1/2,0\nu\beta\beta})^{-1} = G_{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$, where $\langle m_{\beta\beta}\rangle^2 \equiv |\sum_i U_{ei}^2 m_i|^2$. $G_{0\nu}$ is a phase space factor, m_i is the mass of neutrino mass eigenstate ν_i, and $M_{0\nu}$ is the transition nuclear matrix element. The matrix element has significant nuclear theoretical uncertainties, dependent on the nuclide under consideration.

In the standard three-massive-neutrinos paradigm,

$$\langle m_{\beta\beta}\rangle = |\cos^2\theta_{12}\cos^2\theta_{13}e^{-2i\xi}m_1 + \sin^2\theta_{12}\cos^2\theta_{13}e^{-2i\zeta}m_2 + \sin^2\theta_{13}e^{-2i\delta}m_3|. \tag{1.12}$$

If none of the neutrino masses vanish, $\langle m_{\beta\beta}\rangle$ is a function of not only the oscillation parameters $\theta_{12,13}, \delta$ and the neutrino masses $m_{1,2,3}$ but also the two Majorana phases ξ, ζ. Neutrino oscillation experiments indicate that at least one neutrino has a mass of ~ 45 meV or more. As a result and as shown in Fig. 1-18, in the inverted hierarchy mass spectrum with $m_3 = 0$ meV, $\langle m_{\beta\beta}\rangle$ is between 10 and 55 meV depending on the values of the Majorana phases. This region is sometimes referred to as the atmospheric mass scale region. Exploring this region requires a sensitivity to half-lives exceeding 10^{27} years. This is a challenging

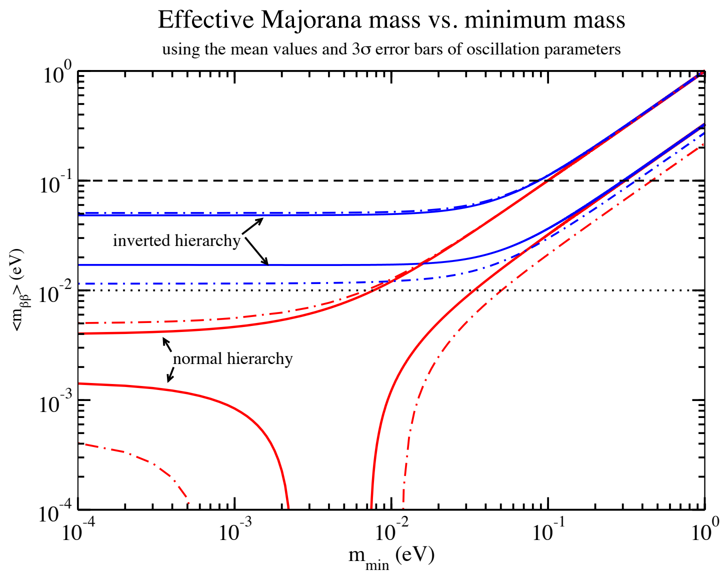


Figure 1-18. *Allowed values of $\langle m_{\beta\beta}\rangle$ as a function of the lightest neutrino mass for the inverted and normal hierarchies. The regions defined by the solid curves correspond to the best-fit neutrino mixing parameters from [**?**] and account for the degeneracy due to the unknown Majorana phases. The regions defined by the dashed-dotted curves correspond to the maximal allowed regions including mixing parameter uncertainties as evaluated in [**?**]. The dashed line shows expected sensitivity of next-generation ∼100 kg class experiments and the dotted line shows potential reach of multi-ton scale future experiments.*

goal requiring several ton-years of exposure and very low backgrounds. The accomplishment of this goal requires a detector at the ton scale of enriched material and a background level below 1 count/(ton y) in the spectral region of interest (ROI). Very good energy resolution is also required.

There is one controversial result from a subset of collaborators of the Heidelberg-Moscow experiment, who claim a measurement of the process in ^{76}Ge, with 70 kg-years of data [**?**]. These authors interpret the observation as giving an $\langle m_{\beta\beta}\rangle$ of 440 meV. Recent limits using the isotope ^{136}Xe from EXO-200 and KamLAND-Zen (see below) are in tension with this $\langle m_{\beta\beta}\rangle$ regime.

There is a large number of current neutrinoless double-beta decay search efforts, employing very different techniques; a recent review is [**?**]. Here we will highlight some for which there is a component of effort from physicists based in the US. These represent different kinds of detectors and experimental approaches [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**].

The Majorana [**?**, **?**, **?**, **?**] experiment employs the germanium isotope ^{76}Ge, to be enriched. The current phase of the experiment is the "Demonstrator", which will employ 30 kg of Ge enriched to 86% ^{76}Ge and 10 kg of Ge P-type point contact detectors, is being constructed underground at the Sanford Underground Research Facility (SURF). It will have first data in 2013 with data from enriched detectors in 2014. The Majorana collaboration is planning a ton-scale effort in collaboration with its European counterpart GERDA.

The "bolometric" CUORE experiment [**?**, **?**], located at Gran Sasso National Laboratory in Italy, employs ^{130}Te in the form of natural TeO_2 crystals. This is a cryogenic setup, operated at temperatures around 10 mK, that determines the energy deposit via temperature rise measured with thermistors. Bolometric detectors are characterized by excellent energy resolution (5 keV FWHM has been achieved) and high efficiency for electrons from the double-beta decay. The prototype of this experiment, Cuoricino, ran from 2003-2008 with 11.3 kg of ^{130}Te mass. The first stage of CUORE, CUORE-0, is currently operating with a ^{130}Te mass of 11 kg, and the full CUORE detector plans commencing operations in 2014 with 206 kg. CUORE aims at the sensitivity to the $0\nu\beta\beta$ lifetime of 2×10^{26} after five years of operation, which would correspond to about the middle of the Inverted hierarchy region.

The EXO experiment [?] makes use of ^{136}Xe, which double-beta decays as $^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} + \text{e}^- + \text{e}^-$. The first version of EXO, EXO-200, is currently taking data at the Waste Isolation Pilot Plant in New Mexico with 200 kg of xenon enriched to 80% in the isotope 136. A time projection chamber is used to detect both scintillation light from the interaction and ionization energy deposited by the electrons in the xenon, which is used in the liquid phase. EXO-200 reported the first observation of the two-neutrino double-beta decay [?] in ^{136}Xe and subsequently a limit on the neutrinoless double beta decay [?] in ^{136}Xe. The EXO collaboration is planning a 5-ton detector called nEXO that builds on the success of the EXO-200 detector. The expected nEXO sensitivity to the $0\nu\beta\beta$ half-life is 2.5×10^{27} years after 10 years of operation. The EXO collaboration's novel idea for an upgrade is the use of barium tagging: the principle is to reduce backgrounds by identifying the resulting nucleus by laser spectroscopy [?]. This ambitious plan– to tag a single ion in 5 tons of xenon – is currently under development, and there are several schemes under development, including gaseous versions of EXO. The incorporation of barium tagging will improve the nEXO senstivity to the $0\nu\beta\beta$ half-life by approximately an order of magnitude.

Another ambitious idea for a double-beta decay experiment is SNO+ [?, ?]. SNO+ is an experiment at SNOlab in Canada which plans to refill the acrylic vessel of SNO with liquid scintillator. This experiment would in addition provide a rich physics program of solar neutrino, geoneutrino and supernova neutrino physics (see Sec. 1.9). SNO+ plans to load the scintillator with 0.3% Te, which after one year of data should give them a 90% C.L. sensitivity of approximately 4×10^{25} years (neutrino mass sensitivity of 70 to 100 meV). There is an R&D effort underway to increase the amount of Te loaded into the scintillator, which could allow complete coverage of the inverted hierarchy.

KamLAND-Zen [?] (the Kamioka Liquid Anti-Neutrino Detector, ZEro Neutrino double-beta decay experiment) is an extension of the KamLAND[?] experiment. KamLAND is a 6.5-m radius balloon filled with 1000 tons of liquid scintillator, surrounded by 3000 tons of mineral oil and submerged inside a 9-m radius stainless-steel sphere with PMTs mounted on the wall. In 2011, the collaboration added an additional low-background miniballoon into the inner sphere that contains 13 tons of liquid scintillator loaded with 330 kg of dissolved Xe gas enriched to 91% in ^{136}Xe. The initial results include an improved limit on neutrinoless double-beta decay for ^{136}Xe and a measurement of two-neutrino double-beta decay that agrees with the recent EXO-200 result [?]. The collaboration is currently in the process of purifying the Xe-LS of a problematic background observed in the first phase of data taking. The collaboration has an additional 400 kg of enriched Xe in hand and is considering options to upgrade the detector with a larger-size internal balloon.

NEXT [?, ?, ?] (Neutrino Experiment with Xenon TPC) intends to use >100 kg of Xe enriched to $\sim$90% in ^{136}Xe. The detector will be a moderate-density gas TPC $\sim$0.08 g/cm^3 that will detect primary and secondary scintillation light. By operating at low pressures ($\sim$15 bar), the design should not only provide good energy resolution, but also permit tracking that allows fairly detailed track reconstruction to confirm that candidate events involve two electrons moving in opposite directions. The collaboration has recently demonstrated impressive 1% resolution at 662 keV in a limited fiducial volume device. Construction started in 2012 with commissioning scheduled to start in 2014. It will operate at the Laboratorio Subterráneo de Canfranc (LSC) in Spain.

The SuperNEMO [**?**, **?**] proposal builds on the great success of the NEMO-3 (Neutrino Ettore Majorana Observatory) experiment, which measured two-neutrino double-beta decay rates and set some of the most stringent constraints for zero-neutrino double beta transitions for seven isotopes [**?**]. NEMO-3 has provided some of the best two-neutrino double-beta decay data to date, including information on single-electron energy distributions and opening angles. The design uses calorimetry to measure energies and timing, and tracking to provide topological and kinematical information about the individual electrons. SuperNEMO will improve on NEMO-3 by using a larger mass of isotope, lowering backgrounds, and improving the energy resolution. The present design is for 100 kg of ^{82}Se, but other isotopes, like ^{150}Nd or ^{48}Ca, are also being considered. It will have a modular design of 20 thin-source planes of 40 mg/cm^2 thickness. Each source will be contained within a Geiger-mode drift chamber enclosed by scintillator and phototubes. Timing measurements from digitization of the scintillator and drift chamber signals will provide topological information such as the event vertex and particle directionality. The modules will be surrounded by passive shielding. A one-module demonstrator with 7 kg of ^{82}Se is planned to be commissioned in 2014. One of the Demonstrator's goal is to reach a zero-background regime in the energy region of interest around the double-beta-decay transition energy ($2.8-4.5$ MeV for ^{82}Se, ^{150}Nd, and ^{48}Ca, respectively). The complete experiment will be ready by the end of the decade in an extension of the LSM Modane in the Fréjus Tunnel in France. Its design sensitivity for the $0\nu\beta\beta$ half-life of ^{82}Se is 10^{26} yr, in a 500 kg·yr exposure.

The current and next-generation experiments are of 10-100 kg masses; these have sensitivities down to about 100 meV. Further ton-scale experiments are planned for the generation beyond that: these should have sensitivities reaching the 10 meV or smaller scale. Reaching this regime will be very interesting in its complementarity with oscillation experiments: if independent oscillation experiments (or data from supernovae or colliders) determine the mass hierarchy to be inverted, and there is no $0\nu\beta\beta$ decay signal at the 10 meV scale, then neutrinos must be Dirac (assuming Nature is not too diabolical). If a signal is observed at the few meV scale, then not only will we know that neutrinos are Majorana, but we will also know that the hierarchy must be normal, even in the absence of an independent determination.

It is important to understand that several experiments using different isotopes are in order, at each step of sensitivity. This is because different isotopes involve different matrix elements with their uncertainties. In addition, unknown small-probability gamma transitions may occur at or near the end point of a particular isotope, but it is very unlikely that they occur for *every* double-beta decay emitter. Finally, and maybe most importantly, different isotopes generally correspond to radically different techniques, and since neutrinoless double-beta decay searches require exceedingly low backgrounds, it is virtually impossible to decide *a priori* which technique will truly produce a background-free measurement. The long-term future for double-beta decay experiments will depend on what is observed: if no experiments, or only some experiments, see a signal at the 100 kg scale, then ton-scale experiments are in order. If a signal is confirmed, the next generation of detectors may be low-energy trackers, in order to better investigate the $0\nu\beta\beta$ mechanism by separately measuring the energies of each electron as well as their angular correlations.

Experiment	Isotope	Mass	Technique	Status	Location
AMoRE[?, ?]	^{100}Mo	50 kg	$CaMoO_4$ scint. bolometer crystals	Devel.	Yangyang
CANDLES[?]	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL[?]	^{48}Ca	1 ton	CaF_2 scint. crystals	Devel.	Solotvina
COBRA[?]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0[?]	^{130}Te	11 kg	TeO_2 bolometers	Constr. (2013)	Gran Sasso
CUORE[?]	^{130}Te	203 kg	TeO_2 bolometers	Constr. (2014)	Gran Sasso
DCBA[?]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Devel.	Kamioka
EXO-200[?, ?]	^{136}Xe	200 kg	Liq. ^{enr}Xe TPC/scint.	Op. (2011)	WIPP
nEXO[?]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SNOLAB
GERDA[?]	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Op. (2011)	Gran Sasso
GSO[?]	^{160}Gd	2 t	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Devel.	
KamLAND-Zen[?, ?]	^{136}Xe	400 kg	^{enr}Xe dissolved in liq. scint.	Op. (2011)	Kamioka
LUCIFER[?, ?]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Devel.	Gran Sasso
MAJORANA [?, ?, ?]	^{76}Ge	30 kg	^{enr}Ge semicond. det.	Constr. (2013)	SURF
MOON [?]	^{100}Mo	1 t	^{enr}Mo foils/scint.	Devel.	
SuperNEMO-Dem[?]	^{82}Se	7 kg	^{enr}Se foils/tracking	Constr. (2014)	Fréjus
SuperNEMO[?]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal (2019)	Fréjus
NEXT [?, ?]	^{136}Xe	100 kg	gas TPC	Devel. (2014)	Canfranc
SNO+[?, ?, ?]	^{130}Te	800 kg	Te-loaded liq. scint.	Constr. (2013)	SNOLAB

Table 1-4. *A summary list of neutrinoless double-beta decay proposals and experiments.*

1.6 Weighing Neutrinos

1.6.1 Kinematic neutrino mass measurements

The neutrino's absolute mass cannot be determined by oscillation experiments, which give information only on mass differences. The neutrino's rest mass has a small but potentially measurable effect on its kinematics, in particular on the phase space available in low-energy nuclear beta decay. The effect is indifferent to the distinction between Majorana and Dirac masses, and independent of nuclear matrix element calculations.

Two nuclides are of major importance to current experiments: tritium (^{3}H or T) and ^{187}Re. The particle physics is the same in both cases, but the experiments differ greatly. Consider the superallowed decay $^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$. The electron energy spectrum has the form:

$$dN/dE \propto F(Z,E) p_e (E + m_e)(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2} \tag{1.13}$$

where E, p_e are the electron energy and momentum, E_0 is the Q-value, and $F(Z,E)$ is the Fermi function. If the neutrino is massless, the spectrum near the endpoint is approximately parabolic around E_0. A finite neutrino mass makes the parabola "steeper", then cuts it off m_ν before the zero-mass endpoint. The value of m_ν can be extracted from the shape without knowing E_0 precisely, and without resolving the cutoff.

The flavor state ν_e is an admixture of three mass states ν_1, ν_2, and ν_3. Beta decay yields a superposition of three spectra, with three different endpoint shapes and cutoffs, whose relative weights depend on the magnitude of elements of the mixing matrix. Unless the three endpoint steps are fully resolved, the spectrum is well approximated by the single-neutrino spectrum with an effective mass $m_\beta^2 = \Sigma_i U_{ei}^2 m_i^2$. Past tritium experiments have determined $m_\beta < 2.0$ eV.

To measure this spectrum distortion, any experiment must have the following properties:

- High energy resolution—in particular, a resolution function lacking high-energy tails—to isolate the near-endpoint electrons from the more numerous low-energy electrons.
- An extremely well-known spectrometer resolution. The neutrino mass parameter covaries very strongly with the detector resolution.
- The ability to observe a very large number of decays, with high-acceptance spectrometers and/or ultra-intense sources, in order to collect adequate statistics in the extreme tail of a rapidly-falling spectrum.

1.6.2 Upcoming experiments

KATRIN The KATRIN experiment [?, ?], now under construction, will attempt to extract the neutrino mass from decays of gaseous T_2. KATRIN achieves high energy resolution using a MAC-E (Magnetic Adiabatic Collimation-Electrostatic) filter. In this technique, the T_2 source is held at high magnetic field. Beta-decay electrons within a broad acceptance cone are magnetically guided towards a low-field region; the guiding is adiabatic and forces the electrons' momenta nearly parallel to B field lines. In the parallel region, an electrostatic field serves as a sharp energy filter. Only the highest-energy electrons can pass the filter and reach the detector, so MAC-E filters can tolerate huge low-energy decay rates without encountering detector rate problems. In order to achieve high statistics, KATRIN needs a very strong source, supplying 10^{11} e^-/s to the spectrometer acceptance. This cannot be done by increasing the source thickness, which is limited by self-scattering, so the cross-sectional area of the source and spectrometer must be made very large, 53 cm^2 and 65 m^2 respectively. As proposed, KATRIN anticipates achieving a neutrino mass exclusion limit down to 0.2 eV at 95% confidence, or 0.35 eV for a 3-sigma discovery.

KATRIN is currently under construction. As of March 2013, the KATRIN spectrometer (i.e. the MAC-E filter) is fully instrumented, baked, and pumped down to 6×10^{-11} mbar. The detector system is operational. The spectrometer/detector system will be calibrated with an electron gun starting in summer 2013. The tritium source is on-track for installation in 2014, and data-taking will begin in late 2015.

Project 8 Project 8 is a new technology for pursuing the tritium endpoint [?]; it anticipates providing a roadmap towards a large tritium experiment with new neutrino mass sensitivity, via a method with systematic errors largely independent of the MAC-E filter method. In Project 8, a low-pressure gaseous tritium source is stored in a magnetic bottle. Magnetically-trapped decay electrons undergo cyclotron motion for $\sim 10^6$ orbits. This motion emits microwave radiation at frequency $\omega = qB/\gamma m$, where γ is the Lorentz factor. A measurement of the frequency can be translated into an electron energy. A prototype, now operating at the University of Washington, is attempting to detect and characterize single conversion electrons from a ^{83m}Kr conversion electron calibration source. The prototype is intended to help answer a number of technical questions, including the merits of various magnetic-trap configurations for the electrons, waveguide vs. cavity configurations for the microwaves, and questions about data analysis techniques.

The Project 8 collaboration will follow up on this prototype by preparing detailed proposals for larger experiments. A first experiment would aim for few-eV neutrino mass sensitivity while precisely measuring other parameters of the decay spectrum. A larger followup experiment would extend the sensitivity down to the limits of the technique.

Microcalorimeter methods While most of the neutrino-mass community is focused on tritium, there are several other nuclides of potential experimental interest. Tritium is the only low-energy beta decay nuclide whose decay rate (and low atomic number) permits the creation of thin, high-rate sources. If one can detect decays in a cryogenic microcalorimeter, the requirement of a thin source is removed, and one can explore lower-energy decays. For a neutrino mass m_ν and a beta-decay energy E_0, the fraction of decays in the signal region scales as $(m_\nu/E_0)^3$. The best-known candidate is ^{187}Re, whose beta-decay endpoint is unusually low at 2.469 keV. However, the long lifetime of ^{187}Re forces any such experiment to instrument a very large total target mass, and the low-temperature properties of Re are unfavorable.

Another candidate, ^{163}Ho, is somewhat more promising. In the EC decay $^{163}\text{Ho} \rightarrow {}^{163}\text{Dy}$, the inner bremsstrahlung spectrum is sensitive to the neutrino mass. Speculation [?] that atomic effects might enhance the endpoint phase space has been largely resolved. At the moment, however, even ambitious microcalorimeter proposals require long data-taking periods to accumulate statistics with sub-eV sensitivity, and the systematic errors are underexplored.

PTOLEMY The PTOLEMY experiment [?] at Princeton is attempting to combine many different technologies in a single tritium-endpoint spectrometer. While its primary goal is the detection of relic neutrinos, as discussed in Sec. 1.9.1, its measurements would certainly be relevant to a direct search for neutrino masses. The PTOLEMY design uses a thin surface-deposition tritium source, which in a future design is planned to reach 100 g. Tritium beta electrons are accelerated into a static MAC-E filter which discards all but the last 50–150 eV of the spectrum. The remaining electrons, now at a manageable event rate, are time-tagged by detection of their RF cyclotron radiation in a long solenoid. Finally, the electrons are decelerated to energies below 1 keV before detection in a cryogenic microcalorimeter. The calorimeter provides both energy information at 0.1 eV resolution, and time-of-flight information in correlation with the RF tagger. PTOLEMY installed a small technology-validation prototype at the Princeton Plasma Physics Laboratory in February 2013. The collaboration plans to use the prototype to measure the spectrum of tritium deposited on different substrates including titanium, gold, diamond, and graphene.

Several of PTOLEMY's methods are untested and may present serious practical challenges. The use of a solid-state source will require a careful roadmap towards answering systematic-error questions.

Cosmological probes Another way of addressing the question of absolute neutrino masses connects to the cosmic frontier. The field of observational cosmology now has a wealth of data. Global fits to the data – large-scale structure, high-redshift supernovae, cosmic microwave background, and Lyman α forest measurements – yield limits on the sum of the three neutrino masses of less than about 0.3-0.6 eV, although specific results depend on assumptions. Future cosmological measurements will further constrain the absolute mass scale. References [**?**, **?**, **?**] are recent reviews. The Planck experiment has very recently published new global cosmology fits, including strong neutrino mass constraints, discussed in Sec. [**?**].

1.6.3 Mass-measurement milestones and their physics implications

There is substantial complementarity between kinematic measurements, neutrinoless double beta decay measurements, and cosmological constraints.

Kinematic measurements are sensitive to m_β, a simple mixing-weighted sum with a nonzero lower bound. Neutrinoless double beta decay is either (a) insensitive to $m_{\beta\beta}$, if neutrinos are Dirac particles, or (b) if neutrinos are Majorana, sensitive to $m_{\beta\beta}$, a quantity which incorporates masses, mixing angles, and complex phases, and may in certain cases be zero. Cosmological probes are in sensitive to the simple sum of masses, independent of mixing angles and symmetries, but this sensitivity could be garbled by changes to the cosmological assumptions, including (but not limited to) new fundamental physics.

One worthwhile question is, under what circumstances do direct measurements resolve the neutrino mass hierarchy? See Fig. 1-19. Direct measurements based on beta decay are intrinsically capable of unambiguous determination of the hierarchy because they can identify the three masses weighted by their electron flavor content. However, the mass resolution to make such a measurement is well beyond present capabilities for any choice of mass or hierarchy. A measurement at the achievable sensitivity represented by KATRIN, 200 meV, would show that neutrinos have a nearly degenerate hierarchy, perhaps even more interesting from the theoretical standpoint than the level ordering. In the foreseeable future, new ideas such as Project 8 may be able to reach the 50 meV level. Non-observation of the mass at this level would show that the hierarchy is normal.

1.6.4 Future progress and needs for absolute neutrino mass measurements

The field of direct neutrino mass determination, with KATRIN leading the push to $\sim$0.2 eV sensitivity, is balancing both statistical and systematic errors. Experiments aiming for lower masses, including Project 8 and PTOLEMY, take it for granted that large statistical power is needed. However, attention must be

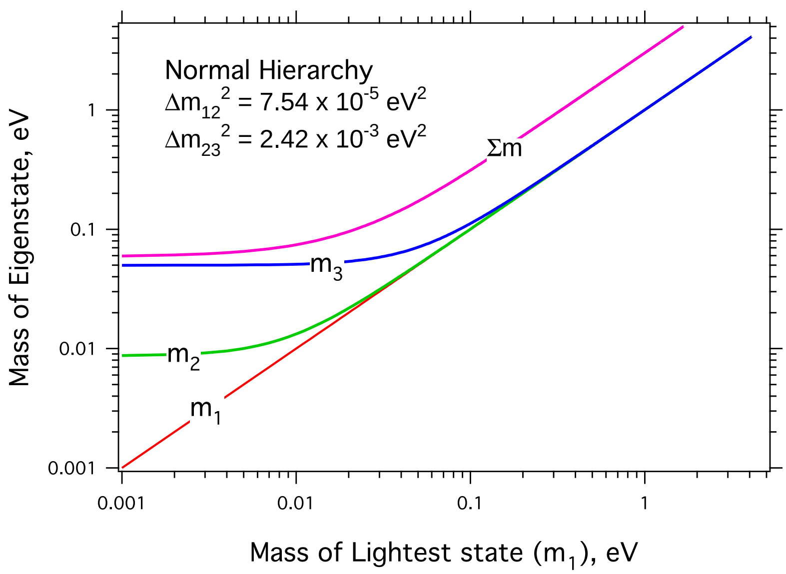


Figure 1-19. *For normal hierarchy, m_β vs. m_{min} and component mass eigenstates.*

paid to systematics. One systematic error in particular, the molecular excited-state distribution of the daughter ion (in $T_2 \rightarrow (T\ ^3He)^{+*} + e^- + \bar{\nu}_e$) produces an irreducible smearing of all T_2 decay spectra; this smearing is presently unmeasured, and known (with an uncertainty difficulty to quantify) from quantum theory. The effect is present in common in KATRIN, Project 8, and any future T_2-based experiment. The field would benefit from an experimental verification or a theory cross-check on these excited-state spectra. Technologies allowing high-purity atomic T_0 sources would be an end-run around this uncertainty. Most other systematic errors in T_2 experiments are technology-specific, which is important for robust comparisons between experiments.

On the microcalorimeter side, the field is benefiting from decades of hard work, largely on the astrophysics side, in developing microcalorimeter arrays. The discovery of the favorable ^{163}Ho spectrum highlights the need to complete a search for other candidate nuclides, including high-precision mass measurements to resolve ambiguities about several low-Q decays.

1.7 Neutrino Scattering

1.7.1 Introduction

Predictions for the rates and topologies of neutrino interactions with matter are a crucial component in many current investigations within nuclear and astroparticle physics. Ultimately, we need to measure neutrino-matter interactions precisely to enable adequate understanding of high-priority physics including neutrino oscillations, supernova dynamics, and dark matter searches. Precise knowledge of such neutrino interactions is an absolute necessity for future measurements of the masses and mixings mediating neutrino oscillations. To enable further progress in neutrino physics, we eventually need to understand, fairly completely, the underlying physics of the neutrino weak interaction within a nuclear environment. This completeness is required so that we can reliably apply the relevant model calculations across the wide energy ranges and varying nuclei necessary for our neutrino investigations.

Neutrino cross section uncertainties are already becoming a limiting factor in the determination of neutrino oscillation parameters in many experiments. Furthermore, experiments using heavier nuclear targets to increase their signal yields have to contend with the presence of significant nuclear effects impacting both the interaction cross sections and observed final states. Such nuclear effects also impact the reconstruction of the incoming neutrino energy, a key quantity in the determination of neutrino oscillation parameters. Understanding these neutrino-nucleus scattering processes directly affects how well one can separate signal from background. Uncertainties in both the neutrino interaction cross sections and associated nuclear effects must be understood to maximize the sensitivity of an experiment to neutrino oscillations. Of course, depending on the detector, the scientific question being asked, and the oscillation parameters, different cross section uncertainties can take on different levels of importance. For example, careful control of neutrino/antineutrino cross section differences will be particularly important in establishing CP violation in the neutrino sector [?]. In fact, since $|U_{e3}|$ is larger than minimal assumptions, such systematic uncertainties become even more important because the expected neutrino/antineutrino asymmetry becomes increasingly smaller for larger $|U_{e3}|$.

In addition to the goal of better understanding neutrino-nucleus interactions for more precise oscillation measurements, we also need this physics under control for undertanding the dynamics of supernovae. The physics of core-collapse supernova is not yet well-understood. Neutrinos are likely very important in the dynamics of supernovae as well as valuable probes into their inner workings. Supernova neutrinos can also be used to measure oscillations as they travel from source to large detectors on earth, if we can accurately quantify their interactions with nuclei within these large detectors.

These and related physics topics are most easily categorized according to the energy of the incident neutrino. The 0.2-10 GeV energy range (called "intermediate-energy" here) is of most relevance to current and planned meson decay-in-flight (DIF) neutrino beams such as those being used currently for ICARUS, MicroBooNE, MINOS, NOvA, OPERA, T2K, and in the future for LBNE. In addition, a beam from stored muons such as in a muon-factory or the currently proposed nuSTORM facility [?] would also elucidate this regime. The 10-100 MeV range ("low-energy") is relevant for supernova neutrino studies. Such low energy neutrinos can be produced in intense beams of lower energy protons that create copious pions that decay at rest (DAR). The physics of interest that is categorized by these energy ranges corresponds (with some overlap between) to the type of neutrino source.

1.7.2 Intermediate-Energy Regime

In the 0.2-10 GeV neutrino energy regime, neutrino interactions are a complex combination of quasi-elastic scattering, resonance production, and deep inelastic scattering processes, each of which has its own model and associated uncertainties. Solar and reactor oscillation experiments operating at very low neutrino energies and scattering experiments at very high energies have enjoyed very precise knowledge of their respective neutrino interaction cross sections (at the few-percent level) for the detection channels of interest. However, the same is not true for the relevant intermediate energy regime. In this region, the cross sections even off free nucleons are not very well measured (at the $10-40\%$ level) and the data are in frequent conflict with theoretical predictions. Furthermore, the nuclear effects ranging from multi-nucleon-target initial states to complex final-state interactions are still quite poorly known. Figure 1-20 shows existing measurements of charged-current neutrino cross sections in the relevant energy range. Such measurements form the foundation of our knowledge of neutrino interactions and provide the basis for simulations in present use.

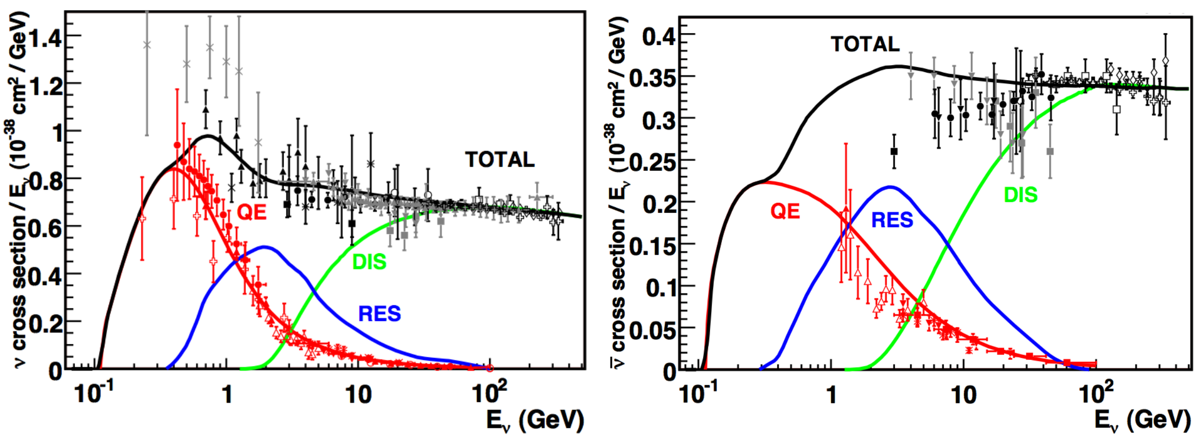


Figure 1-20. *Existing muon neutrino (left) and antineutrino (right) charged-current cross section measurements [?] and predictions [?] as a function of neutrino energy. The contributing processes in this energy region include quasi-elastic (QE) scattering, resonance production (RES), and deep inelastic scattering (DIS). The error bars in the intermediate energy range reflect the uncertainties in these cross sections (typically $10-40\%$, depending on the channel).*

There has been renewed interest and progress in neutrino interaction physics in the last ten years because of recent efforts to understand and predict signal and background rates in neutrino oscillation searches in few-GeV beams. One of several intriguing results from these new data comes from recent measurements of quasi-elastic (QE) scattering. QE scattering is a simple reaction historically thought to have a well-known cross section; this is one reason why it is chosen as the signal channel in many neutrino oscillation experiments. Interestingly, the neutrino QE cross section recently measured on carbon at low energy by the MiniBooNE experiment is about 40% higher than the most widely used predictions [?] and is even larger than the free nucleon scattering cross section in some energy regions [?]. Similar effects are seen for antineutrinos [?]. These results are surprising because nuclear effects have always been expected to reduce the cross section, not enhance it. A recent QE cross section measurement from NOMAD at higher energies does not exhibit such an enhancement [?]. A possible reconciliation between the two classes of measurements has suggested that previously neglected nuclear effects could in fact significantly increase the QE cross section on nuclei at low energy [?]. A similar enhancement has been observed in electron-nucleus scattering [?]. If true, this radically changes our thinking on nuclear effects and their impact on low energy neutrino interactions. This revelation has been the subject of intense theoretical scrutiny and experimental investigation over the past year or more (see for example, [**?**, **?**, **?**, **?**]).

In the so-called resonance/transition region, the channels of interest are mainly hadronic resonances with the most important being the $\Delta(1232)$. Typical final states are those with a single pion. During the last five years, several new pion production measurements have been performed. In all of them, the targets were nuclei (most often carbon). As one example, the MiniBooNE experiment recently measured a comprehensive suite of CC $1\pi^+$, CC $1\pi^0$, and NC $1\pi^0$ production cross sections [**?**]. A variety of flux-integrated differential cross sections, often double differential, were reported in various final state particle kinematics. The cross section results differ from widely-used predictions at the 20% level or more.

These recent results illustrate that neutrino-nuclei interactions are quite complex, especially in the energy regime where we are conducting our neutrino oscillation measurements. There are still significant differences between experimental results and the predictions of current event generators. Modern data are uncovering new and unexpected phenomena, but more data and increased levels of theoretical effort are required for future progress.

There are several efforts currently producing results that will add significantly to the available data and to the underlying physics understanding. The MINERvA experiment in the 1-10 GeV NuMI beam at Fermilab has very recently published results on QE scattering measured with a precise tracking detector from both neutrino and antineutrinos on carbon [**?**, **?**]. The near detectors of the T2K [**?**] experiment in Japan are also measuring neutrino-nucleus interactions as part of their oscillation measurement program. T2K has recently reported total cross sections for neutrino CC inclusive scattering [**?**]. Additional results on exclusive channels from MINERvA and both the T2K and NOvA near detectors will be forthcoming in the near future.

The MINERvA experiment will also perform the first studies of nuclear effects in neutrino interactions using a suite of nuclear targets including He, C, O (water), Fe, and Pb in addition to a large quantity of scintillator CH. Analysis of neutrino scattering processes from these varying nuclei are already underway. Another possible step in the MINERvA program is the addition of a deuterium target [**?**] which is currently under review. This is an intriguing, albeit challenging, possibility as it will allow nuclear effects in these processes to be separated from the bare-nucleon behavior.

All current accelerator-based neutrino experiments use a meson-decay beam either on-axis or off-axis to narrow the energy spread of the beam. The uncertainty in the neutrino flux normalization and spectral shape will ultimately limit our understanding of the underlying physics of neutrino interactions and the ability to conduct precision neutrino oscillation measurements. Because of these uncertainties, an improved understanding of our neutrino beams is paramount. For these beams, some improvement in the knowledge of the neutrino flux is possible through meson production experiments that determine the underlying meson momentum and angular distributions. These can then be combined with detailed simulations of the neutrino beamline optics. Current neutrino fluxes are known to the 10% level with a goal to reach the 5% level or better.

In combination, neutrino rates in these beams should be made whenever possible. Additional experiments in beams of different energies provide a valuable cross-check on the underlying energy dependence of physics models as well as the background calculations of the experiments. For example, the NOvA experiment, which will soon run in the NuMI off-axis neutrino beam, offers a unique opportunity to add to the world's neutrino interaction data by measuring cross sections with its near detector as well as with a possible upgrade to a relatively inexpensive fine-grained detector such as the proposed SciNOvA experiment [**?**, **?**].

A potentially transformative next step beyond meson-decay beams as sources of neutrinos would be the use of circulating muon beams. The muons may be either uncooled and unaccelerated as in the case of nuSTORM [**?**] or both cooled and accelerated as in the case of a Neutrino Factory. These facilities will yield a flux of neutrinos known to better than 1%, thus allowing large gains in our understanding of neutrino interaction processes. Another significant advantage of these muon-decay based neutrino sources would be the availability, for the first time, of an intense and well-known source of electron-(anti)neutrinos. Such beams would allow the measurement of ν_e-nucleus cross sections, which have not been historically well measured and are of great importance to future $\nu_\mu \to \nu_e$ oscillation experiments.

In addition to beam improvements, up-and-coming detector technologies such as LAr TPCs will both provide increased tracking precision for better final-state exclusivity as well as measurements specifically on argon. Understanding interactions on argon is obviously crucial for oscillation measurements in LBNE given that the far detector of choice is a LAr TPC. New neutrino scattering measurements on argon are already being reported by ArgoNeuT which ran in the NuMI beam in 2009–2010 [**?**]. The near-future MicroBooNE experiment which will begin taking data in an $\approx$1 GeV neutrino beam starting in 2014 will further boost this effort in the next few years. In addition, other efforts with imminent, $\approx$ 10 ton LAr TPCs [**?**] in an existing beam such as NuMI, can also provide more information on reconstruction and final-state topology to further this effort.

However, in order to adequately map out the complete nuclear dependence of the physics, there is need to have multiple nuclear targets to measure the nuclear effects combined with a precision tracker. For this an attractive follow-on to MINERvA would be a straw-tube/transition-radiation detector that employs multiple nuclear targets (including argon) simultaneously in the same beam such as that proposed for one of the LBNE near-detector options [**?**].

1.7.3 Low-Energy Regime

The 10-100 MeV neutrino energy range addresses a varied set of topics at the forefront of particle physics such as supernovae, dark matter, and nuclear structure. Low-energy neutrino scattering experiments are possibilities at currently-existing high-intensity proton sources such as the ORNL SNS or the Fermilab Booster neutrino beam line. They should also be considered at future facilities such as Project-X at Fermilab.

1.7.3.1 Supernova neutrino physics

The multiple physics signatures and expected neutrino fluxes from a core-collapse signature are described in Sec. 1.9.2.1. The get the most from the next supernova neutrino observation, it will be critical to understand the interactions of neutrinos with matter in the tens-of-MeV energy range [**?**, **?**].

A stopped-pion source provides a monochromatic source of 30 MeV ν_μ's from pion decay at rest, followed on a 2.2 μs timescale by $\bar{\nu}_\mu$ and ν_e with a few tens of MeV from μ decay. The ν spectrum matches the expected supernova spectrum reasonably well (see Fig. 1-21). A $\sim$ 1 GeV, high-intensity, short-pulse-width, proton beam is desirable for creating such a ν source. Prior examples used for neutrino physics include LANSCE and ISIS. A rich program of physics is possible with such a stopped-pion ν source, including measurement of neutrino-nucleus cross sections in the few tens of MeV range in a variety of targets relevant for supernova neutrino physics. This territory is almost completely unexplored: so far only ^{12}C has been measured at the 10% level.

A pion DAR neutrino source such as that currently available at the ORNL SNS neutron spallation target would be an excellent source of neutrinos for this physics on a variety of nuclei relevant for supernova [**?**, **?**]. In addition, this source would allow specific studies to better understand the potential of a large LAr detector such as that proposed for LBNE. In particular, low-energy neutrino-argon cross sections, required

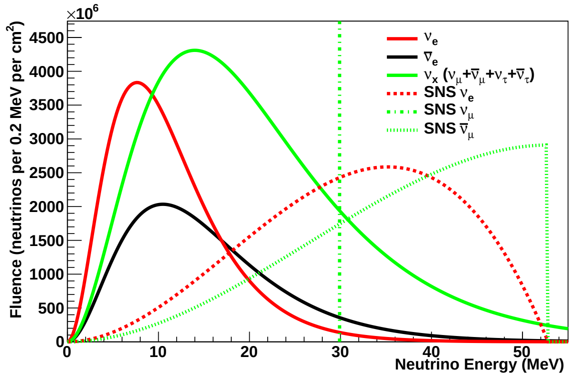


Figure 1-21. *Solid lines: typical expected supernova spectrum for different flavors; fluence integrated over the ∼15-second burst. Dashed and dotted lines: SNS spectrum; integrated fluence for one day at 30 m from the SNS target.*

for supernova detection in a large LAr detector could be measured with a near future prototype ≈ 10 ton LAr detector [?, ?]. In the farther future, the high-intensity FNAL Project-X 1-3 GeV Linac would also provide a potential site for these experiments.

1.7.3.2 Coherent elastic neutrino-nucleus scattering

Coherent elastic neutrino-nucleus scattering (CENNS), a process in which the target nucleus recoils coherently via a collective neutral current exchange amplitude with a neutrino or antineutrino, is a long-sought prediction of the Standard Model. Although the process is well predicted by the Standard Model and has a comparatively large cross section (10^{-39} cm^2) in the relevant energy region ($0 \sim 50$ MeV), CENNS has never been observed before as the low-energy nuclear recoil signature is difficult to observe. Numerous groups world-wide are now working to detect this elusive process. Only a few sources, in particular nuclear reactors and spallation neutrino sources, produce the required 1-50 MeV energies of the neutrinos in sufficient quantities for a definitive first measurement. Above this energy, the de Broglie wavelength of the neutrino approaches that of the individual nucleon and the coherent interaction strength diminishes.

A modest sample of a few hundred events collected with a keV-scale-sensitive dark-matter-style detector could improve upon existing non standard neutrino interaction parameter sensitivities by an order of magnitude or more. A deviation from the ∼5% predicted cross section could be an indication of new physics [?, ?]. Either way, the cross section is relevant for understanding the evolution of core-collapse supernovae, characterizing future burst supernova neutrino events collected with terrestrial detectors, and a measurement of the process that will ultimately set the background limit to direct WIMP searches with detectors at approximately the ten-ton scale [?, ?]. Proposals have arisen to probe nuclear structure [?] owing to the sensitivity of the coherent scatter process to the number of neutrons in the nucleus, and to search for sterile neutrinos [?, ?] by exploiting the flavor-blind nature of the process. There are also potentially practical applications, as described in Sec. 1.10.3.

Well-defined neutrino sources are an essential component to measure CENNS. This experiment may be performed, if a near, low-background location may be identified, at the Spallation Neutron Source at Oak Ridge National Laboratory [?, ?]. As an alternative, there may be an opportunity to utilize the existing FNAL 8 GeV proton source at a far off-axis location [?].

Required Theoretical/Phenomenological Work A strong effort in theory/phenomenology/modeling is requisite to profit from improved measurements in neutrino experiments. While there is a healthy community working on the subject of neutrino-nucleus interactions in Europe, there is a dearth of phenomenologists in the U.S. able to address the pressing theoretical questions needed to fully understand this subject and apply it to the interpretation of experimental data. Even in Europe, the funding for phenomenology work is not necessarily tied to neutrino-nucleus scattering but to other more European-centric physics projects. There is a critical need within the U.S. physics community to devote time and resources to a theoretical/phenomenological understanding of neutrino-nucleus scattering. This naturally directly calls for a united effort of both the particle and nuclear physics communities to better support these efforts [**?**]. There are numerous ideas that have been put forth by both experimentalists and theorists for how best to proceed [**?**]. They include suggestions for improvements to neutrino event generators with more sophisticated underlying calculations for neutrino interactions on nuclei as well as the formation .

1.8 Beyond the Standard Paradigm – Anomalies and New Physics

Neutrinos moved beyond the Standard Model years ago with the discovery of neutrino oscillations which implied the existence of neutrino mass, but since neutrino masses can be accommodated with minor modifications to the Standard Model, the three neutrino mixing paradigm is no longer, or at least not widely, viewed as "new physics". Instead, when we talk about anomalies in neutrino physics we are referring to evidence that does not agree with the standard three-neutrino mixing model. In particular, the marginal yet persistent evidence of oscillation phenomena around $\Delta m^2 \sim 1$ eV^2, which is not consistent with the well-established solar and atmospheric Δm^2 scales, is often interpreted as evidence for one or more additional neutrino states, known as sterile neutrinos. Beyond the sterile neutrino, new physics may appear thorough broad array of mechanisms collectively known as non-standard interactions (NSI). Typically, searches for these effects occur in experiments designed to study more standard phenomena. One type of NSI that has been the subject of dedicated searches in the past and may play a role in the future program is the neutrino magnetic moment. In the following sections we will discuss the prospects for neutrino experiments sensitive to anomalies and new physics over the next several years.

1.8.1 Sterile Neutrinos

Data from a variety of short-baseline experiments as well as astrophysical observations and cosmology hint at the existence of additional neutrino mass states beyond the three active species in the Standard Model (see for example [**?**]). The possible implications of additional sterile neutrino states would be profound, and would change the paradigm of the Standard Model of particle physics. As a result, great interest has developed in testing the hypothesis of sterile neutrinos and providing a definitive resolution to the question: do sterile neutrinos exist?

Recently, a number of tantalizing results (anomalies) have emerged from short-baseline neutrino experiments that cannot be explained by the current three-neutrino paradigm. These anomalies are not directly ruled out by other experiments and include the excess of $\bar{\nu}_e$ events (3.8σ) observed by the LSND experiment [**?**], the ν_e (3.4σ) and $\bar{\nu}_e$ (2.8σ) excesses observed by MiniBooNE [**?**] and particularly at low-energy in ν_e mode [**?**], the deficit of $\bar{\nu}_e$ events (0.937 ± 0.027) observed by reactor neutrino experiments [**?**], and the deficit of ν_e events (0.86 ± 0.05) observed in the SAGE and GALLEX radioactive source experiments [**?**].

Although there may be several possible way to explain these anomalies, the simplest explanations is the $3 + N$ sterile neutrino model, in which there are three light, mostly active neutrinos and N, mostly sterile neutrinos which can mix with the active flavors. For $N > 1$, these models allow for CP-violating effects in short-baseline appearance experiments. The world's oscillation data can be fit to these $3 + N$ models resulting in closed allowed regions at 95% CL or better, as shown in Figs. **??** and **??** for the 3+1 model example. Still, significant tension exists between the appearance and disappearance data [**?**], particularly due to the absence nu_ν disappearance in the $\Delta m^2 \sim 1$ eV^2 region [**?**, **?**], a key prediction of the $3 + N$ models.

Beyond particle physics, there are a hints of additional neutrinos coming from cosmology. Fits to astrophysical data sets including the cosmic microwave background (CMB), large scale structure, baryon acoustic oscillations and big bang nucleosynthesis are sensitive to the effective number of light degrees of freedom (N_{eff}), which in the standard model is equivalent to saying the effective number of neutrino families, although in principle this could include other types of light, weakly-coupled states. Prior to the release of the Planck data in 2013, there was an astonishing trend that such fits, conducted by different groups and involving differing mixes of data sets and assumptions, tended to find N_{eff} closer to 4 than to 3 [**?**]. With the release of Planck data [?] new more precise fits to N_{eff} are more consistent with 3. The Planck Collaboration fits range from 3.30 ± 0.52 (95% CL) to 3.62 ± 0.49 (95% CL) depending on which other data sets are included in the fit. These fits rely heavily on the CMB power spectrum and pre-Planck fits used the full-sky WMAP [?] data set for the first three peaks of the spectrum, but and typically relied on narrow-sky, high angular resolution observations by the South Pole Telescope [?], or the Atacama Cosmology Telescope [?] for the next four peaks. The Planck mission combined a full-sky survey with high angular resolution and was, for the first time, able to measure the first seven peak in the CMB power spectrum with one apparatus. The Planck Collaboration believes that a miscalibration in the stitched together CMB spectra is responsible for the anomalously high value of N_{eff} found in the earlier fits [?]. While the new fits to N_{eff} are more consistent with 3 than before they are still high. Generally they seem to rule out $N_{eff} \geq 4$, but they are still consistent with a 1 or more additional neutrino states that are not fully thermalized.

For a comprehensive review of light sterile neutrinos including the theory, the cosmological evidence, and the particle physics data see Ref. [?].

In order to determine whether these short-baseline anomalies are due to neutrino oscillations in a $3 + N$ sterile neutrino model, future short-baseline experiments are needed. These experiments should have robust signatures electron and/or muon interactions and they should be capable of measuring the L/E dependence of the appearance or disappearance effect. Several ways of measuring L/E dependence have been proposed including: 1) placing a large detector close to a source of low-energy neutrinos from a reactor or intense radioactive source and measuring the L/E dependence of the $\overset{(-)}{\nu}_e$ disappearance in the single detector, 2) positioning detectors at two or more baselines from the neutrino source, and 3) measuring the L/E dependence of high energy atmospheric-induced neutrinos, where strong matter effects are expected, in particular close to the matter resonance expected for the sterile Δm^2 in the Earth's core.

Finally, it is important to note that satisfactorily resolving these short-baseline anomalies is very important for carrying out the 3-flavor neutrino oscillation program described earlier. The two to three sigma effects reported, even if unrelated to sterile neutrinos, at the sub-percent to the several-percent level, are similar in scale and effect to the CP-violation and mass hierarchy signals being pursued in the long-baseline experiments.

1.8.1.1 Projects and Proposals with Radioactive Neutrino Sources

Proposals to use radioactive neutrinos sources to search for sterile neutrino oscillations actually predate the Gallium Anomaly [?]. Perhaps the most attractive characteristic of source experiments is the possibility of precision oscillometry – the imaging, within one detector, of multiple waves in L/E – which means that this approach would likely be the best way to deconvolve the multiple frequencies present with 2 or more sterile neutrinos. Typically these proposals are built around existing detectors with well-measured backgrounds, and the new effort involves creating a source and bringing it to the detector. There are two types of source being actively considered: 1) ^{51}Cr is an electron capture isotope which produces a ν_e of 750 keV, and 2) ^{144}Ce-^{144}Pr in which the long-lived ^{144}Ce ($\tau_{1/2}$ = 285 days) β-decays producing a low energy $\bar{\nu}_e$ of no interest, while the daughter isotope, ^{144}Pr, rapidly β-decays producing a 3 MeV endpoint $\bar{\nu}_e$. Since they are mono-energetic, ^{51}Cr neutrinos can be detected by charged current, neutral current or elastic scattering, because there is no need to reconstruct the neutrino energy. On the other hand, ^{144}Pr neutrinos, which are emitted with a β spectrum, must be detected via a charged current process. In particular, inverse β-decay with its 1.8 MeV threshold is used.

Proposals actively under consideration include **SOX** [?] based on the Borexino detector, **Ce-LAND** [?] based on the KamLAND detector, and a **Daya Bay Source** experiment [?]. SOX is considering both ^{51}Cr

Table 1-5. *Proposed sterile neutrino searches.*

Experiment	ν Source	ν Type	Channel	Host	Cost Catagory[1]
Ce-LAND [?]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	Kamioka, Japan	small[2]
Daya Bay Source [?]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	China	small
SOX [?]	^{51}Cr	ν_e	disapp.	LNGS, Italy	small[2]
	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.		
US Reactor [?]	Reactor	$\bar{\nu}_e$	disapp.	US[3]	small
Stereo	Reactor	$\bar{\nu}_e$	disapp.	ILL, France	NA[4]
DANSS [?]	Reactor	$\bar{\nu}_e$	disapp.	Russia	NA[4]
OscSNS [?]	π-DAR	$\bar{\nu}_\mu$	$\bar{\nu}_e$ app.	ORNL, US	medium
LAr1 [?]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
MiniBooNE+ [?]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	small
MiniBooNE II [?]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab	medium
ICARUS/NESSiE [?]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	CERN	NA[4]
IsoDAR [?]	^{8}Li-DAR	$\bar{\nu}_e$	disapp.	Kamioka, Japan	medium
νSTORM [?]	μ Storage Ring	$\overset{(-)}{\nu}_e$	$\overset{(-)}{\nu}_\mu$ app.	Fermilab/CERN	large

[1] Rough recost categories: small: <$5M, medium: $5M-$50M, large: $50M-$300M.
[2] US scope only.
[3] Multiple sites are under consideration [?].
[4] No US participation proposed.

and a ^{144}Ce-^{144}Pr phases. In the ^{51}Cr phase, a source of up to 10 MCi is located about 8 m from the center of the detector. This phase takes advantage of Borexino's demonstrated ability to see the elastic scattering of 861 keV solar ν_e from ^{7}Be decay [?]. Later phases may involve a ^{144}Ce-^{144}Pr source which could be located either inside or outside the detector, the former requiring major modifications to Borexino. Ce-LAND and the Daya Bay Source proposals are both based on ^{144}Ce-^{144}Pr. In the Daya Bay Source proposal, a 500 kCi source is placed in between the four 20-ton antineutrino detectors at the Daya Bay Far site. With Ce-LAND, a 75 kCi source could be placed either outside the detector, 9.5 m from the center, of inside the detector, but only after the KamLAND-Zen $\beta\beta_{0\nu}$ run is complete. The sensitivity for these experiments is shown in Fig. 1-22a. There is also the possibility of a sterile neutrino measurement based on the combination of a ^{51}Cr source with cryogenic solid state bolometers, to detect any active neutrino flavor through neutral current coherent neutrino-nucleon scattering [?]. This proposal, known as **RICOCHET**, would be a direct test of the sterile hypothesis since the neutral current is equally sensitive to all active flavors, but blind to any sterile neutrinos.

1.8.1.2 Projects and Proposals that Directly Address the Reactor Anomaly

The apparent deficit of neutrinos in short-baseline neutrino experiments, known as the reactor anomaly is result of two distinct lines of analysis. First, there are the calculations of reactor antineutrino flux [?, ?, ?, ?], which are based on measurements of the β-spectra from the relevant fission isotopes [?, ?], and second, there are the reactor antineutrino measurements [?, ?, ?, ?, ?, ?, ?, ?, ?]. The anomaly [?] emerges in the comparison of these two analyses, and as such it can be tested from both directions.

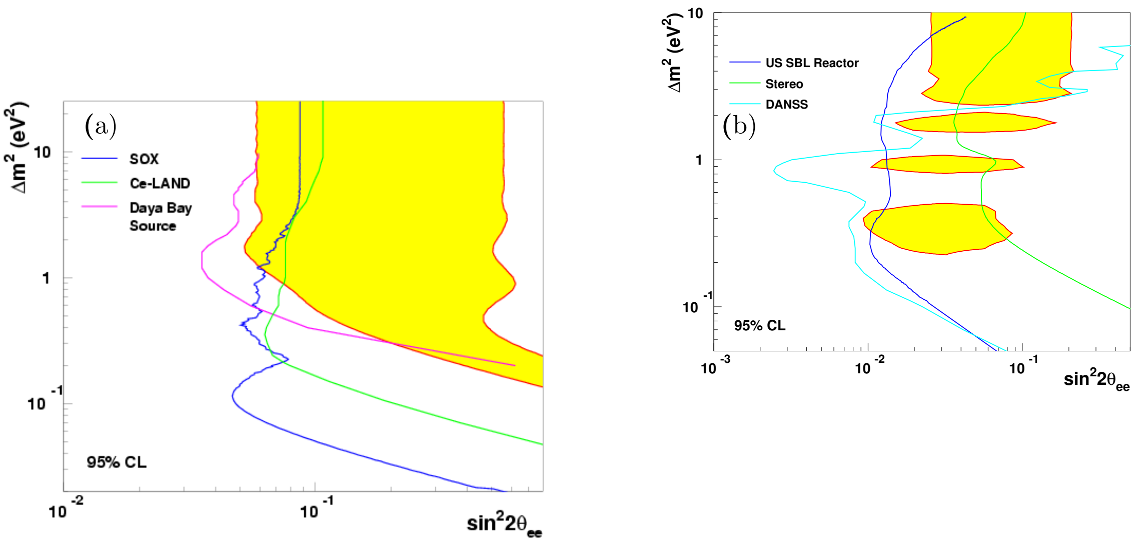


Figure 1-22. *Collaboration-reported sensitivity curves for proposed source (a) and reactor (b) experiments plotted against the global fits [?] for the gallium anomaly and reactor anomaly respectively.*

The most direct proof of a sterile neutrino solution to the reactor anomaly would be to observed a spectral distortion in the antineutrino rate that varies as a function of distance from the reactor core. There are several projects and proposals from all over the world to search for this effect, including: **Stereo** [?] at ILL in France and **DANSS** [?] at the Kalinin Power Plant in Russia, to name two. In the US, the parties interested in this measurement have organized into a single collaboration [?] that is investigating several possibilities [?] and detector technologies [?]. A compact reactor core is highly desirable to reduce the smearing and uncertainty in L, which makes power reactors less attractive. In addition, new detector designs with better spatial resolution and improved neutron tagging may be needed.

On the antineutrino flux side, the existing reactor θ_{13} experiments, such as **Daya Bay** [?], with their high-statistics near detectors at baselines far enough to average out any spectral distortions from sterile oscillations, will provide the world's best data on reactor fluxes, ensuring that the uncertainty on the reactor anomaly is dominated by the flux calculation. New measurements of the β-spectra of the fission isotopes [?], would be helpful in further reducing the uncertainty on the flux calculation, but theoretical uncertainties from effects such as weak magnetism [?] will ultimately limit this approach.

1.8.1.3 Projects and Proposals with Accelerator Induced Neutrinos

There are a number of proposals involving Fermilab's Booster Neutrino Beam (BNB) which are relevant to the sterile neutrino question. Currently under construction right upstream of MiniBooNE, the **MicroBooNE** experiment will use the fine grain tracking of its 170 ton LAr TPC to study in detail the interaction region of events corresponding to the MiniBooNE low-energy excess, and therefore determine if these $\nu_\mu \to \nu_e$ oscillation candidates are really charged current quasielastic events as assumed by MiniBooNE. Similarly, the proposed **MiniBooNE+** [?] would look for neutron captures following ν_e candidate events. In the MiniBooNE energy range the production of free neutrons in a neutrino interaction is strongly correlated with the charged current. MiniBooNE+ would search for these neutrons by adding scintillator to the MiniBooNE detector making it sensitive to the 2.2 MeV gammas produced when a neutron captured on hydrogen. This neutron tagging capability can be used to study whether the MiniBooNE low-energy excess events are truly ν_e events as the oscillation hypothesis requires. The **MiniBooNE II** proposal [?], to either build a new near detector or move the existing MiniBooNE detector to a near location, is also intended as a test of MiniBooNE excess. The presence of a near detector could confirm or refute the baseline dependence of the excess. The LAr1 proposal [?] is a multi-baseline proposal for the BNB which is based on LAr. The **LAr1** proposal would add a 25-ton, "MicroLAr" detector at 100 m and a 3 kton, "LAr1", detector at 700 m to the existing MicroBooNE detector, which is at a baseline of 470 m. The projected sensitivity of this three detector combination is shown in Fig. 1-23b. There is also a less ambitious proposal to add just the MicroLAr near detector [?]. In Fermilab's NuMI beam line the **MINOS+** experiment [?] will search for muon neutrino to sterile disappearance.

There is also a proposal for a two detector LAr TPC at CERN known as **ICARUS/NESSiE** [?]. In this proposal, the ICARUS T600 LAr TPC would be moved from Gran Sasso and set 1600 m downstream from a new neutrino beam in the CERN-SPS. A second, smaller LAr TPC would be build at 300 m. A muon spectrometer would be installed behind each TPC. The projected sensitivity of ICARUS/NESSiE is shown in Fig. 1-23b.

The Spallation Neutron Source (SNS) facility at Oak Ridge National Laboratory produces an intense and well-understood flux of neutrinos from π^+ and μ^+ decay at rest in much the same way as LAMPF produced neutrinos for LSND [?]. As such it is an excellent place to conduct a direct test of the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation signal. The **OscSNS** [?] proposal, would build an 800-ton detector approximately 60 m from the SNS beam dump. OscSNS could improve upon LSND in at least three specific ways: 1) the lower duty factor of the SNS would significantly reduce cosmic backgrounds, 2) the detector could be placed up steam of the beam lowering the possibility of non-neutrino beam correlated backgrounds, and 3) the use of gadolinium to capture neutrons would provide a more robust tag of inverse β-decay. In addition to $\bar{\nu}_e$ appearance, OscSNS would be capable of searching for ν_μ and ν_e disappearance. The projected sensitivity of the OscSNS $\bar{\nu}_e$ appearance search is shown in Fig. 1-23b.

IsoDAR [?] is a proposal to use a low-energy, high-power cyclotron to produce ^{8}Li, which β-decays producing a $\bar{\nu}_e$ with an endpoint of 13 MeV. These neutrinos would be detected via inverse β-decay in the KamLAND detector. This arrangement would be sensitive to the disappearance of $\bar{\nu}_e$, and given the low-energy of the neutrinos and 13-m detector diameter it should be possible to do oscillometry. The projected sensitivity of IsoDAR is shown in Fig. 1-23a.

The **nuSTORM** [?] proposal, to build a racetrack shaped a muon storage ring, would provide clean and well characterized beams of both electron and muon neutrinos (or antineutrinos depending on which sign of muons is stored). These beams would enable extremely precise searches for sterile neutrino oscillations in all four types of neutrinos, and in both appearance and disappearance channels. The most powerful and unprecedented capability of nuSTORM would be to search for $\overset{(-)}{\nu}_\mu$ appearance. The nuSTORM beams are essentially free of intrinsically produced wrong sign/wrong flavor neutrinos which are present in every pion decay-in-flight beam, but muon storage ring beams do contain both ν_μ and $\bar{\nu}_e$ (or $\bar{\nu}_\mu$ and ν_e) simultaneously, making it essential to have magnetic detectors to distinguish between oscillated and beam neutrinos. The baseline nuSTORM design has near and far magnetized iron detectors, but future upgrades could include magnetized LAr TPCs. The nuSTORM facility, which, in addition to sterile neutrino searches, would make neutrino cross section measurements critical to the long-baseline program (see Sec. 1.7) and conduct neutrino factory R&D, is based on existing accelerator technology. Proposals for nuSTORM are currently being considered by both Fermilab and CERN. The projected sensitivity of the nuSTORM $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu$ search is shown in Fig. 1-23b.

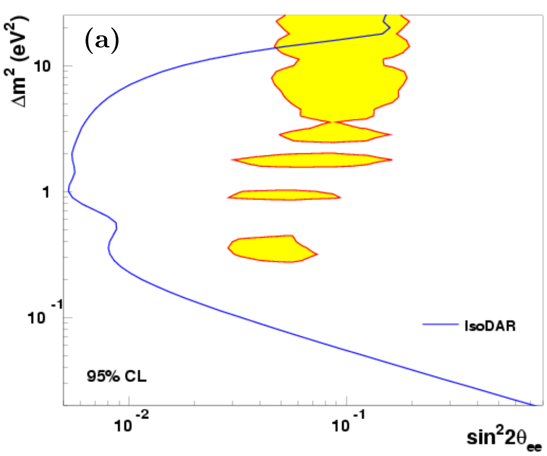
1.8.1.4 Sensitivity from Atmospheric Neutrinos

The disappearance of atmospheric ν_μ in the 0.5 to 10 TeV energy range can be enhanced by matter effects in the Earth's core for the case of a sterile neutrino with $\Delta m^2 \sim 1$ eV^2 [?, ?]. Such neutrinos are observed by the **IceCube** experiment [?] at the South Pole, and by studying the zenith angle (effectively L) dependance of any disappearance effect they can measure or set limits on the muon to sterile mixing amplitude.

1.8.2 Non-Standard Interactions

Neutrino experiments in general, and neutrino oscillation experiments in particular, are also very sensitive to new, heavy degrees of freedom that mediate new "weaker-than-weak" neutral current interactions. These so-called non-standard interactions (NSI) between neutrinos and charged fermions modify not only neutrino production and detection, but also neutrino propagation through matter effects. In a little more detail, NSI are described by effective operators proportional to, for example, $G_F\epsilon^f_{\alpha\beta}\nu_\alpha\gamma_\mu\nu_\beta\bar{f}\gamma^\mu f$, where $\nu_{\alpha,\beta} = \nu_{e,\mu,\tau}$, f are charged fermions $(e, u, d, \mu, s, \ldots)$, G_F is the Fermi constant, and ϵ are dimensionless couplings.[6] When f is a first-generation fermion, the NSI contribute to neutrino detection and production at order ϵ^2 (ignoring potential interference effects between the Standard Model and the NSI). On the other hand, the NSI also contribute to the forward-scattering amplitude for neutrinos propagating in matter, modifying the neutrino

[6] $\epsilon \sim 1$ ($\ll 1$) implies that the new physics effects are on the order of (much weaker than) those of the weak interactions.



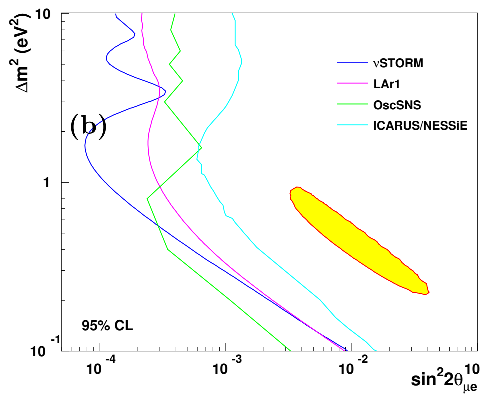


Figure 1-23. *Collaboration reported sensitivity curves for proposed accelerator-based experiments sensitive to ν_e and $\bar{\nu}_e$ disappearance (a) and appearance which includes $\nu_\mu \to \nu_e$ and $\nu_e \to \nu_\mu$ in both neutrinos and antineutrinos, (b) plotted against the global fits [**?**].*

dispersion relation and hence its oscillation length and mixing parameters. These modified matter effects are of order ϵ^1 and potentially more important than the NSI effects at production or detection. Furthermore, for $\alpha \neq \beta$, the NSI-related matter effects lead to $P_{\alpha\beta} \neq \delta_{\alpha\beta}$ in the very short baseline limit ($L \to 0$), which are not present in the Standard Model case. More information – including relations to charged-lepton processes – current bounds, and prospects are discussed in detail in, for example, [**?**, **?**], and references therein.

1.8.3 Neutrino Magnetic Moment

In the minimally extended standard model, the neutrino magnetic moment is expected to be very small ($\mu_\nu \sim 10^{-19} - 10^{-20}\ \mu_B$) [**?**]. As such it makes the neutrino magnetic moment a great place to look for new physics. The current best limit of $\mu_\nu < 3.2 \times 10^{-11}\ \mu_B$ at 90% CL comes from the GEMMA experiment at the Kalinin Nuclear Power Plant in Russia [**?**]. Generally, many models for new physics could allow for a NMM just below the current limit. The NMM can be related to the Dirac neutrino mass scale by naturalness arguments such that the mass scale is proportional to the product of μ_ν and the energy scale of new physics, which implies that $|\mu_\nu \leq 10^{-14}\ \mu_B$ for Dirac neutrinos [**?**]. NMM for Majorana neutrinos suffer from no such constraint. Therefore a discovery of NMM of as much as a few orders of magnitude below the current limit would imply that neutrinos are Majorana particles.

Laboratory searches for NMM are based on neutrino-electron elastic scattering, in the scattering rate is studied as a function of electron recoil energy (T). Below the maximum recoil energy, the weak differential cross section ($d\sigma/dT$) is essentially flat, while for the electromagnetic cross section is inversely proportional to T [**?**]. The reactor experiments, which are responsible for the best terrestrial limits, are unable to detect the elastic scattering rate over background, but can nevertheless set limits based on the non-observation of an increasing rate at low T. The reactor experiments are clearly limited by the background environment present at the surface and by constraints on detector size imposed by the limited space close to a reactor and the need for massive shielding. On the other hand, experiments based on radioactive neutrinos sources, such as the ^{51}Cr source discussed in the context of sterile searches, do not suffer from these limitations. Sources can be paired with proposed or existing detectors in deep underground laboratories with cavities large enough for kton-scale detectors and their gamma-ray shielding. In particular, dark matter detectors, such as **LUX** [**?**] and **CoGeNT** [**?**], which are designed to be sensitive to nuclear recoils with electron equivalent energies of a few keV, would be excellent for such NMM searches. Additionally, it may be possible to use a single ^{51}Cr source simultaneously for sterile neutrino and NMM searches.

1.9 Neutrinos in Cosmology and Astrophysics

Neutrinos come from astrophysical sources as close as the Earth and Sun, to as far away as distant galaxies, and even remnants from the Big Bang. They range in kinetic energy from less than one meV to greater than one PeV, and can be used to study properties of the astrophysical sources they come from, the nature of neutrinos themselves, and cosmology.

1.9.1 Ultra-low-energy neutrinos

The Concordance Cosmological Model predicts the existence of a relic neutrino background, currently somewhat colder than the cosmic microwave background, $T_\nu = 1.95$ K. While relic neutrinos have never been directly observed, their presence is corroborated by several cosmological observables that are sensitive to the amount of radiation in the universe at different epochs. For example, precision measurements of the cosmic microwave background, and measurements of the relic abundances of light elements, independently require relativistic degrees of freedom other than photons, that are compatible with the three known neutrino species of the Standard Model of particle physics [**?**, **?**]. Interestingly, a number of recent measurements – although well consistent with the Standard Model – seem to slightly favor a larger amount of radiation, compatible with four light neutrinos. This suggests a connection with the fact that a number of anomalies at neutrino experiments also favor the existence of a fourth "sterile" light neutrino (see Sec. 1.8). While any conclusion is premature, the question of a possible excess of cosmic radiation will be clarified by future, more precise, measurements of this quantity.

The cosmological relic neutrinos constitute a component of the dark matter, and their properties determine the way they contribute, with the rest of the dark matter, to the formation of large scale structures such as galactic halos. In particular, their mass has a strong impact on structure formation. This is because, being so light, neutrinos are relativistic at the time of decoupling and their presence dampens the formation of structure at small distance scales. The heavier the neutrinos, the more they influence structure formation, and the less structure is expected at small scales. Data are consistent with 100% cold dark matter and therefore give an upper bound on the total mass of the three neutrino species: $\sum m_i < 0.7$ eV, approximately (see e.g., [**?**]). This bound should be combined with the lower limit from oscillation experiments: $\sum m_i > 0.05$ eV (Sec. 1.4), which sets the level of precision that next-generation cosmological probes must have to observe effects of the relic neutrino masses. At this time, prospects are encouraging for answering this question.

Deviations from the Concordance Cosmological Model or new physics beyond the Standard Model of fundamental particles can dramatically modify the relationship between cosmological observables and neutrino properties. The extraction of neutrino properties from cosmological observables is, in some sense, complementary to that from terrestrial experiments. By comparing the results from these two classes of experimental efforts, we can not only determine properties of the massive neutrinos, including exotic ones, but also hope to test and, perhaps, move beyond the Concordance Cosmological Model.

The "holy grail" of neutrino astrophysics/cosmology is the direct detection of the relic neutrino background. This is extremely cold (1.95 K $= 1.7 \times 10^{-5}$ eV) and today, at least two of the neutrino species are nonrelativistic. Several ideas have been pursued, and a clear path towards successfully measuring relic neutrinos has yet to emerge. Recently, the idea, first discussed in [**?**], of detecting relic neutrinos through threshold-less inverse-beta decay – e.g., $\nu_e + ^3\mathrm{H} \to ^3\mathrm{He} + e^-$ – has received some attention [**?**]. In a nutshell, the β-rays produced by the relic neutrino capture have energies above the end point of the β-rays produced by the ordinary nuclear decay. The expected number of interactions turns out to be accessible for intense enough nuclear samples, coupled with technology for very high resolution energy measurements. Specific experimental setups have been proposed recently (e.g. PTOLEMY [?], also see Sec. 1.6.2).

1.9.2 Low-energy neutrinos

Sources of low energy, MeV range, astrophysical neutrinos include the earth, the sun, and core-collapse supernova. Since neutrinos only interact weakly they are unique messengers from these sources allowing us to probe deep into the astrophysical body. The following three distinct detector types proposed in the near future would be sensitive to low-energy neutrino physics: liquid scintillator detectors, water Cherenkov detectors, and liquid argon time projection chambers. Each detector type has particular advantages. Especially in the case of supernova neutrinos, a combination of all types would allow for a better determination of all the potential science. Many of these low-energy signals are sensitive to backgrounds. One background that is poorly understood is muon-induced neutrons. A dedicated program to measure neutron production and transportation within various materials would have a large impact on multiple neutrino and dark-matter experiments both currently running and proposed [?].

1.9.2.1 Physics and Astrophysics with Low-Energy Neutrinos

Solar neutrinos Despite the tremendous success of previous solar-neutrino experiments there are still many unanswered questions, *e.g.* such as what is the total luminosity in neutrinos [?]? what is the metallicity of the Sun's core [?]? The answers to these questions could change our understanding of the formation of the Solar System and the evolution of the Sun. Precise measurements of *pep* or *pp* neutrinos are required to answer the first question, and precise measurements of CNO neutrinos could answer the second question. Solar neutrinos, however, are also ideal probes for studying neutrino oscillation properties. The importance of previous solar neutrino experiments for understanding neutrino properties has been described in Sec. 1.4. New experiments, particularly at the energy of the *pep* neutrinos, would be very sensitive to nonstandard physics. An observation of a day-versus-night difference in the solar neutrino rate would conclusively demonstrate the so-called MSW effect [?, ?].

Geoneutrinos Closer to home, the Earth is also a potent source of low-energy antineutrinos produced in the decay of uranium, thorium and potassium. Precise measurements of the flux of these neutrinos would allow for the determination of the amount of heat-producing elements in the earth (see, for example, [?]), which is currently only estimated through indirect means. Knowing the amount of heat-producing elements is important for our understanding of convection within the earth, which is ultimately responsible for earthquakes and volcanoes. The most recent measurements from KamLAND [?] and Borexino [?] are reaching the precision where they can start to constrain earth models. However, more detectors would be required as these detectors are not sensitive to the neutrino direction and are therefore sensitive to local variations. Ultimately we are interested in knowing the amount of heat producing elements in the earth's mantle, and hence a detector located on the ocean floor away from neutrinos produced in continental crust would be ideal.

Supernova neutrinos Supernovae are thought to play a key role in the history of the universe and in shaping our world. For example, modern simulations of galaxy formation cannot reproduce the structure of the galactic disk without taking the supernova feedback into account. Shock waves from ancient supernovae triggered further rounds of star formation and dispersed heavy elements, enabling the formation of stars like

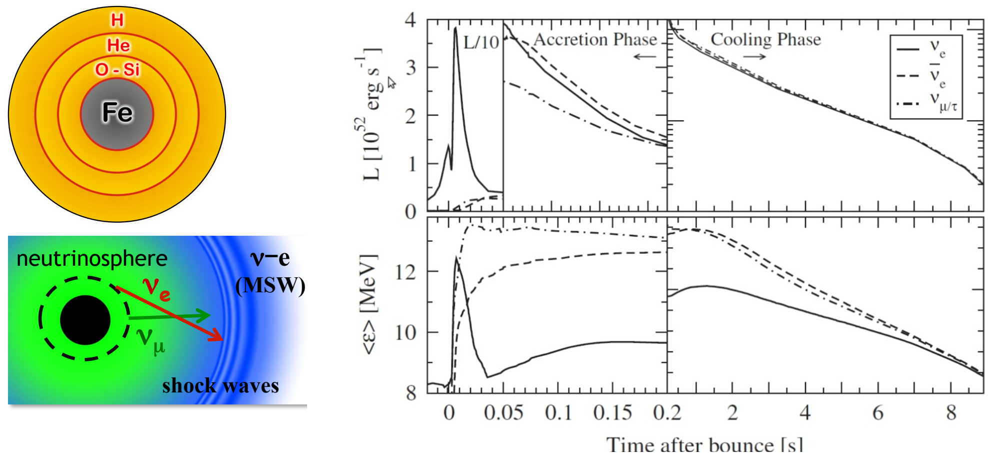


Figure 1-24. *Supernova explosions create an extreme environment with rich physics including matter-enhanced oscillations, collective neutrino effects, and shock phenomena (left). Neutrino fluxes from supernovae encode imprints of the explosion (right). High-statistics measurements of the time distribution as well as the energy spectrum of supernova neutrino fluxes may allow the determination of the mass hierarchy. A variety of detection channels with different thresholds and sensitivities will be required for identifying the oscillation effects and distinguishing supernova models and astrophysical effects. The effect of the mass hierarchy on the diffuse supernova neutrino background appears to be too small to be distinguishable from astrophysical effects. Figures from [**?**, **?**]*

our Sun. Approximately 99% of the energy released in the explosion of a core-collapse supernova is emitted in the form of neutrinos. One of the first questions is what is the mechanism for supernova explosion. Supernova neutrinos record the information about the physical processes in the center of the explosion during the first several seconds, as the collapse happens. Extracting the neutrino luminosities, energy spectra, and cooling timescale would also allow us to study the equation of state of the nuclear/quark matter in the extreme conditions at the core of the collapse. Supernovae provide an incredibly rich source for the understanding of neutrino interactions and oscillations. As neutrinos stream out of the collapse core, their number densities are so large that their flavor states become coupled due to the mutual coherent scattering. This "self-MSW" phenomenon results in non-linear, many-body flavor evolution and has been under active exploration for the last five years, as supercomputers caught up with the physics demands of the problem (see, for example [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**].) While the full picture is yet to be established, it is already clear that the spectra of neutrinos reaching Earth will have spectacular nonthermal features. Neutrino flavor evolution is also affected by the moving front shock and by stochastic density fluctuations behind it, which may also imprint unique signatures on the signal. All of these features will give new large detectors a chance to observe neutrino oscillations in qualitatively new regimes, inaccessible on Earth, and will very likely yield information on the neutrino mass hierarchy (see Sec. 1.4.1.1). Last but not least, the future data will allow us to place significant constraints on many extensions of particle physics beyond the Standard Model. This includes scenarios with weakly interacting particles, such as axions, Majorons, Kaluza-Klein gravitons, and others (see, for example [**?**, **?**]). These new particles could be produced in the extreme conditions in the core of the star and could modify how it evolves and cools. Compared to the 1987A event, when only two dozen neutrinos were observed, future detectors may register tens – or even hundreds – of thousands of neutrino interactions. Furthermore, flavor sensitivity – not only interaction rate but the ability to tag different interaction channels– is critical for maximizing the science harvest from a burst observation.

The neutrino burst from a core-collapse supernova will consist of neutrinos of all flavors with energies in the few tens of MeV range [?]. Because of their weak interactions, the neutrinos are able to escape on a timescale of a few tens of seconds after core collapse (the promptness enabling a supernova early warning for astronomers). An initial sharp "neutronization burst" of ν_e (representing about 1% of the total signal) is expected at the outset, from $p + e^- \rightarrow n + \nu_e$. Subsequent neutrino flux comes from NC $\nu\bar{\nu}$ pair production. Electron neutrinos have the most interactions with the proto-neutron star core; $\bar{\nu}_e$ have fewer, because neutrons dominate in the core; ν_μ and ν_τ have yet fewer, since NC interactions dominate for these. The fewer the interactions, the deeper inside the proto-neutron star the neutrinos decouple and the deeper, the hotter. So one expects generally a flavor-energy hierarchy, $\langle E_{\nu_{\mu,\tau}} \rangle > \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$.

While a single supernova in our galaxy could be expected to produce a large signal in a next-generation neutrino detector, such events are relatively rare (1-3 per century). However, it could also be possible to measure the flux of neutrinos from all the supernovae in cosmic history. The flux of these "diffuse supernova neutrino background" (DSNB) depends on the historical rate of core collapse, average neutrino production, cosmological redshift effects and neutrino oscillation effects [?, ?].

1.9.2.2 Low-energy neutrino detectors

Liquid scintillator detectors Depending on the depth, radiogenic purity, and location, large liquid scintillator detectors could be sensitive to geoneutrinos; *pep*, *pp*, CNO, ^{8}B solar neutrinos; and supernova neutrinos. The majority of the liquid scintillator experiments consist of large scintillator volumes surrounded by light detectors. The Borexino [?] ($\sim$ 300 tons) and KamLAND [?] ($\sim 1,000$ tons)experiments continue to operate. The SNO+ experiment [?] ($\sim$ 900 tons) is currently under construction at SNOLAB, in Sudbury, Canada, and the Daya Bay II experiment ($\sim$ 20,000 tons) [?] is currently approved in China. The Hanohano experiment [?] ($\sim 20,000$ tons) to be located on the ocean floor, and the LENA experiment [?] ($\sim 50,000$ tons) to be located in Europe have been proposed.

The Borexino Collaboration recently announced the first positive measurement of *pep* neutrinos [?], along with a nontrivial upper bound on neutrinos from the CNO cycle, which are yet to be observed. Because of its greater depth, the SNO+ experiment could make a precise measurement of the *pep* neutrinos [?]. Unlike the other experiments, the LENS experiment [?] currently being planned consists of a segmented detector doped with In, which would allow precise measurement of the entire solar neutrino energy spectrum.

Geoneutrinos were first observed in liquid scintillator detectors [?, ?] and all planned scintillator experiments would be sensitive to geoneutrinos, although the location of the Daya Bay II experiment next to nuclear power plants would make such a measurement very difficult. The Hanohano experiment located on the ocean floor would be the ideal geoneutrino experiment.

All of the scintillator detectors would be sensitive to supernova neutrinos, primarily $\bar{\nu}_e$ through neutron inverse beta decay, but also ν_x neutrinos through proton scattering provided their thresholds are low enough [?]. The Hanohano and LENA detectors would also allow a measurement of the DSNB.

Water Cherenkov detectors Depending on the depth and radiogenic purity, large water-Cherenkov detectors could be sensitive to ^{8}B solar neutrinos and supernova neutrinos. The Super-K [?] ($\sim 50,000$ tons, still operating) and SNO [?] experiments ($\sim 1,000$ tons, completed operation) have measured ^{8}B solar neutrinos flux to better than 5% and measured neutrino oscillations with a precision of better than 5%. A measurement of the day versus night asymmetry would require increased statistics. The proposed Hyper-K detector [?] ($\sim 990,000$ tons) would allow for a measurement of the day versus night asymmetry with a significance better than 4σ.

The tremendous size of the Hyper-K detector would result in $\sim 250,000$ interactions from a core collapse supernova at the galactic center, and ~ 25 interactions from a core collapse supernova at Andromeda. The large number of events in a galactic supernova would allow for very sensitive study of the time evolution of the neutrino signal. Although the IceCube detector could not detect individual events from a core collapse supernova, the large volume of ice visible the photomultiplier tubes would result in a detectable change in the photomultiplier hit rates, allowing for a study of the time evolution of a supernova [?].

The addition of Gd to the Super-K [?] or Hyper-K detectors would allow for the study of DSNB within the range of most predictions for the total flux.

Liquid argon time projection chambers A large-enough liquid argon time projection chamber located underground could provide invaluable information about a galactic core-collapse supernova. Unlike other detectors, the principle signal would be due only to electron neutrino interactions, for which unique physics and astrophysics signatures are expected [?]. For a supernova at 10 kpc approximately 1000 events would be expected per 10 kton of liquid argon.

Table 1-6. *Summary of low energy astrophysics detectors. **indicates significant potential, and * indicates some potential but may depend on configuration.*

Detector Type	Experiment	Size (kton)	Status	Solar	Geo	Supernova
Liquid scintillator	Borexino	0.3	Operating	**	**	*
Liquid scintillator	KamLAND	1.0	Operating	**	**	*
Liquid scintillator	SNO+	1.0	Construction	**	**	*
Liquid scintillator	JENO	20	Design/R&D	*	*	**
Liquid scintillator	Hanohano	20	Design/R&D	*	**	**
Liquid scintillator	LENA	50	Design/R&D	*	**	**
Liquid scintillator	LENS	0.12	Design/R&D	**		*
Cherenkov	Super-K	50	Operating	**		**
Cherenkov	IceCube	2000	Operating			**
Cherenkov	Hyper-K	990	Design/R&D	**		**
Liquid Argon	LBNE	35	Design/R&D	*		**

1.9.3 Neutrinos of GeV to PeV Energies

One of the most tantalizing questions in astronomy and astrophysics, namely the origin and the evolution of the cosmic accelerators that produce the observed spectrum of cosmic rays, which extends to astonishingly high energies, may be best addressed through the observation of neutrinos. Because neutrinos only interact via the weak force, neutrinos travel from their source undeflected by magnetic fields and unimpeded by interactions with the cosmic microwave background, unlike photons and charged particles. Due to the low fluxes expected, the construction of high energy neutrino telescopes requires the instrumentation of large natural reservoirs, a concept demonstrated by AMANDA, Baikal and ANTARES. With the completion of the IceCube Neutrino Telescope [?] in the South Polar icecap in 2010, the era of kilometer scale neutrino telescopes has dawned, and plans for a complementary telescope in the Mediterranean are under development. Already, IceCube has demonstrated astrophysical sensitivity by placing severe constraints on favored mechanisms for gamma-ray bursts [?], and cascade events exceeding 1 PeV have been observed [?], which may be a first glimpse of either a new source, or new physics.

As with previous generations of neutrino telescopes, these instruments are expected to provide insight into the nature of the messengers themselves. The background for the astrophysical fluxes sought include atmospheric neutrinos, which are collected by IceCube at a rate of about 100,000 per year in the 0.1 to 100 TeV range. Atmospheric neutrinos provide a probe of neutrino physics and interactions at energies that have been previously unexplored. At TeV energies, the sensitivity of IceCube data to sterile neutrinos in the eV mass range potentially exceeds that of any other experiment and is only limited by systematic errors. With the addition of IceCube's low-energy infill array, Deep Core [?], which extended its energy sensitivity down to 10 GeV, conventional neutrino oscillations have been observed at the 1 sigma level, and it is hoped that such instruments could provide competitive precision measurements of neutrino oscillation parameters. The copious atmospheric neutrino flux may someday also provide a glimpse into our Earth via neutrino radiography.

These instruments may also shed light on one of the most puzzling questions facing particle physics and cosmology: the nature of the dark matter. Dark matter annihilations in the Sun and the galactic center could be indirectly detected in neutrino telescopes, covering a region of parameter space that is inaccessible at the LHC, and masses inaccessible to direct detection experiments. Neutrino telescopes have also been active in the search for other exotica, such as magnetic monopoles.

1.9.4 Neutrinos at Energies Over 1 PeV

At ultra high energies, neutrinos could be detected in dense, radio frequency (RF) transparent media via the Askaryan effect [?, ?]. The abundant cold ice covering the geographic South Pole, with its exceptional RF clarity, has been host to several pioneering efforts to develop this approach, including RICE [?] and ANITA [?]. Currently, two discovery scale instruments are in the prototyping phase: the Askaryan Radio Array (ARA) [?], which is envision to instrument a 100 square kilometer area near the South Pole with 200m deep antenna clusters, and ARIANNA [?], which would be installed on the surface of the Ross Ice Shelf. Efforts are underway to characterize the ice in Greenland, to determine its suitability as a site for a future cosmogenic neutrino telescope.

The fact that cosmic rays have been observed at energies in excess of 10^{20} eV makes the search for neutrinos at these energies particularly tantalizing. These energies are above the threshhold for pion photoproduction on the cosmic microwave background, which would seem to guarantee a flux of ultra high energy neutrinos. However, the neutrino flux expectations are sensitive to the composition of the ultra-high-energy (UHE) cosmic rays, making the spectrum of UHE cosmic rays a sensitive probe of the heavy ion content. In addition, if a sufficient sample of UHE neutrinos were amassed, it would be possible to measure the neutrino cross section at high energies from the zenith angle spectrum.

1.10 Neutrinos and Society

The allure and relevance of neutrino science and technology extends well beyond the fundamental research community. The neutrino signal itself may useful for monitoring reactors in the context of international nuclear nonproliferation, and for Earth tomography. The essential building blocks of neutrino science - detectors and accelerators - have important spin-off applications for medicine and in industry. Finally, ever since neutrinos where first postulated and discovered, their unusual, ghostlike properties and non-intuitive behavior have fascinated the general public. The success of our field depends in no small part on our ability to effectively convey both the mystery and utility of neutrino science to the public, Congress, policy-makers and funding agencies. Below we discuss the direct and spin-off applications, and the rich opportunities for outreach and education offered by fundamental and applied antineutrino science.

1.10.1 Applied Antineutrino Physics

Direct application of neutrinos to other domains falls into two categories. In geology, they may enable study of Earth's composition on largest scales, and in nonproliferation, they offer the prospect of improved monitoring or discovery of operating nuclear reactors. Since the signal in both cases arises from antineutrinos only, it is appropriate to refer to Applied Antineutrino Physics.

As described in Sec. [Nu6], geological applications have been explored in numerous papers, and evidence for a geo-antineutrino signal has been presented by the KamLAND and Borexino collaborations.

Concerning nonproliferation, the main likely user of antineutrino-based reactor monitoring is the International Atomic Energy Agency (IAEA). IAEA is responsible for monitoring the international fuel cycle, to detect attempts to divert fissile materials and production technologies to nuclear weapons programs. The international monitoring regime administered by the IAEA is referred to as the Safeguards regime [?]. Antineutrino detectors may play a role in this regime, which focuses on timely detection of illicit removal of fissile material from known and declared reactors and other fuel cycle facilities, They may also be useful in future expanded regimes, such as the proposed Fissile Material Cutoff Treaty [?], which will seek to verify the non-existence of an undeclared fissile material production capability in a country or geographical region. In a recent report, the IAEA encouraged continued research into antineutrino-detection based applications for safeguards and other cooperative monitoring of nuclear reactors [?]. In addition, the US National Nuclear Security Administration has included a demonstration of remote reactor monitoring (1 km and beyond) as an element of its 2011 Strategic Plan [?].

Nonproliferation applications are enabled by three features of reactor antineutrinos. First, reactors emit a copious flux of ~ 0–10 MeV electron antineutrinos resulting from beta decay of neutron-rich fission fragments. Second, the antineutrino inverse beta cross section is high enough to allow detectors of tractable (cubic meter) sizes to be deployed at tens-of-meter standoff from a reactor. (Much larger but still achievable sizes are required for remote monitoring, scaling roughly as the inverse square of distance, with a subdominant effect due to neutrino oscillations.) Third, the detected antineutrino flux and energy spectrum both correlate with the core-wide content of fission fragments, and through this correlation to the inventories of the main fissile isotopes that are used in weapons. In particular, the emitted antineutrino spectrum relates to the fission rates in the core through the equation

$$\phi_{\bar{\nu}}(E) = \frac{P_{\bar{\nu}_e \bar{\nu}_e}}{L^2} \sum_{i=1}^{4} f_i \phi^i_{\bar{\nu}}(E). \tag{1.14}$$

where $i = {}^{235}\mathrm{U}, {}^{239}\mathrm{Pu}, {}^{238}U, {}^{241}\mathrm{Pu}$ are the four main fissioning isotopes in the core, and $\phi_{\bar{\nu}}(E)$ and $\phi^{i}_{\bar{\nu}}(E)$, are respectively the total emitted antineutrino spectrum and the spectrum for the ith isotope and per fission. f_i is the fission rate for the ith isotope. L is the distance from core to detector, and $P_{\bar{\nu}_e\bar{\nu}_e}$ is the survival probability for the electron antineutrino at this distance. While the individual spectra are fixed, the fission rate of each isotope changes throughout the course of the cycle, in direct proportion to the mass inventories of each fissile isotope. Thus, fissile inventories can be estimated by measuring the differential energy spectrum, and/or its integral throughout some or all of the reactor cycle.

This ensemble of interesting properties lays the groundwork for applications related to tracking and monitoring the flows of fissile material through civil and military fuel cycles, which is the aim of the global nonproliferation regime.

Concerning applications for existing or future reactor safeguards, cubic-meter-scale antineutrino detectors now make it possible to monitor the operational status, power levels, and fissile content of nuclear power reactors in near-real-time with stand-off distances of roughly 100 meters of the reactor core. This capability has been demonstrated at civil power reactors in Russia and the United States, using antineutrino detectors designed specifically for reactor monitoring and safeguards [?, ?]. This near-field monitoring capability may be of use within the International Atomic Energy Agencys (IAEA) Safeguards Regime, and other cooperative monitoring regimes.

With respect to future missions related to remote discovery or exclusion of reactors, current kiloton-scale antineutrino detectors, exemplified by the KamLAND and Borexino liquid scintillator detectors, can allow monitoring, discovery or exclusion of small (few MegaWatt thermal, MWt) reactors at standoff distances up to 10 kilometers. In principle, reactor discovery and exclusion is also possible at longer ranges. However, the required detector masses are 10-100 times greater than the state of the art, and achieving these long range detection goals would require significant research and development. Happily, many elements of the necessary R & D program are already being pursued in the fundamental physics community, as we discuss below.

Numerous articles, reviews, and conferences are devoted to the topic of reactor monitoring with antineutrinos. A partial reading list, including links to a series of annual Applied Antineutrino Physics conferences held since 2004 may be found at [?].

In the following sections we set forth three areas of overlap between topics of strong current interest in the neutrino physics community and technology development aims for antineutrino-based reactor monitoring. An essential and fortunate feature of these activities is that the technology goals are often similar, so that advances in one area are directly applicable in the other.

1.10.2 Inverse Beta Decay detectors for IAEA Near-Field Safeguards Applications, and for Short Baseline Neutrino Oscillation Experiments.

Near-field (10–100 meters) antineutrino monitoring of nuclear reactors is a possible near-term addition to the existing IAEA Safeguards regime. Current IAEA reactor safeguards protocols rely heavily on operator declarations of reactor power and fissile content, and only sparingly on quantitative measurements. Antineutrino monitoring offers a continuous, near-real-time, and non-intrusive quantitative record of power production and plutonium generation of reactors. This "wireless window" into reactor cores provides a reliable, independently measured benchmark for the entire reactor fuel cycle, and serves as a means to detect a range of suspect activities, such as repeated short shutdowns that facilitate removal of plutonium-bearing fuel rods.

The successful demonstrations in Russia and the United States cited above relied on ton scale un-segmented liquid scintillator detectors, which measured the coincident signal from the final state neutron and positron in the inverse beta decay process. To help suppress backgrounds and improve efficiency for the neutron signal, these detectors have been doped with the neutron-capture agent Gadolinium, and taken advantage of relatively shallow depth ($\sim$20-30 mwe) existing galleries at reactor sites.

Antineutrino detectors for near-field monitoring must meet several competing criteria: ease of deployment and operation, the ability to deploy at shallow depths and reject reactor and cosmogenic backgrounds, good detection efficiency, and the ability to precisely and stably measure the antineutrino rate and/or spectrum over the entire 1-2 year long reactor cycle. For the greatest possible independence from input parameters provided by the operator, it is also desirable to measure the antineutrino energy spectrum with as much precision as possible. As a result, good energy resolution is a desideratum if not a requirement.

As discussed in section 1.8, and in numerous Snowmass white papers [**?**], short-baseline neutrino oscillation experiments are being planned by US and overseas groups. These experiments seek to deploy 1–10 ton scale antineutrino detectors from 5–15 meters from a nuclear reactor core. The purpose of the experiments is to search for a possible sterile neutrino signal, and to measure the reactor antineutrino energy spectrum as precisely as possible. The physics goals greatly constrain the experimental configuration. The need for close proximity to the reactor requires that the detector overburden is necessarily minimal, at most $\sim$45 meters water equivalent (mwe). The physical dimension of the core must be as small as possible, to avoid smearing the oscillation-related spectral distortions with multiple baselines arising from different locations in the core. To be competitive with experiments using strong single-element radioactive sources, this requires that a relatively low power ($\sim$20-50 MWt) research reactor be used for the experiment, greatly constraining the number of possible sites.

The above requirements impose stringent constraints on detector design. The minimal overburden and proximity to the reactor both increase backgrounds compared to previous oscillation searches, and demand background rejection capabilities beyond the current state of the art. The detector size is also constrained to be no more than a few tons, owing to the tight space constraints in galleries near reactor cores. In spite of the higher backgrounds and smaller size, the detector efficiency and energy resolution should remain comparable to those achieved in previous oscillation experiments, such as RENO [**?**], Double Chooz [**?**], and Daya Bay [**?**].

The technology goals for reactor short-baseline experiments and for nonproliferation applications are similar in many respects. In both cases, R & D is required to improve background rejection at shallow depths, while maintaining high efficiency and good energy resolution. The energy resolution improvements will come from the use of brighter scintillation media, improved light collection and uniformity of response, including the ability to precisely correct response as a function of position within the detector. Nonlinearities in energy deposition as a function of both energy and particle type must also be properly accounted for. To improve specificity for the two-step inverse beta antineutrino signature, segmented designs [**?**] are being contemplated for both cooperative monitoring and short-baseline detectors, as well as the use of Li-doped plastic or liquid scintillator technologies [**?**].

A key difference between the fundamental and applied technology needs is that the detectors for nonproliferation must also be simple to operate, and may have additional cost constraints compared to the single use detectors needed for the short baseline physics experiments.

1.10.3 CENNS detection for nonproliferation and fundamental science

Numerous physics motivations for the measurement of coherent elastic neutrino-nucleus scattering (CENNS) are described in Sec. 1.7.3.2. For monitoring applications, the process holds considerable interest, since the 100-1000 fold increase in cross section compared with the next most competitive antineutrino interaction may lead to a 10-fold or more reduction in detector volume, even with shielding accounted for. This could simplify and expand the prospects for deployment of these detectors in a range of cooperative monitoring contexts.

Moreover, it is important to recognize that CENNS closely resembles the interaction with nuclei of a leading dark matter candidate, the Weakly Interacting Massive Particle or WIMP. Both are coherent processes which may induce keV scale recoils in a range of detection media. The search for direct interactions of WIMPS in detectors on Earth is the subject of a multiple collaborative efforts in the United States and worldwide. Due to the similarity of the event signature, advances in coherent scatter detection technology will perforce improve the prospects for dark matter detection. Important breakthroughs in sensitivity to light mass WIMPS, or even to electromagnetically interacting dark matter candidates are possible once the coherent neutrino scattering process has been demonstrated. Indeed, at the lowest recoil energies, neutrino-nucleus recoils is likely to prove to be a limiting background for WIMP interactions.

For CENNS detection, both phonon and ionization channel approaches are being pursued. Detector thresholds must be made sufficiently low, while maintaining effective background suppression, so as to allow good collection statistics above background in tractably sized detectors. Lowering of energy thresholds and background suppression and characterization are also goals held in common with many dark matter search programs. In the last few years, several groups worldwide have made significant progress in reducing thresholds in noble liquid [?],[?], and germanium detectors [?], with the intent of improving both coherent scatter and dark matter detectors. White papers focused on discovery of CENNS [?], [?] have been submitted as part of the Snowmass process. For more information on the relevant fundamental and applied science, we refer the reader to a 2012 workshop devoted to these topics [?].

1.10.4 Long-baseline neutrino experiments, supernovae and proton decay, and remote reactor monitoring

One-hundred-kiloton to megaton-scale liquid scintillator and water detectors have been proposed as far detectors for long-baseline accelerator-based neutrino oscillation and CP-violation experiments [?], [?]. If they can be made sensitive to few-MeV antineutrinos, such giant detectors offer an even more diverse physics program, including sensitivity to extra-galactic supernovae, measurement of the diffuse supernova background (see Sec. 1.9), proton decay, and in the case of liquid scintillator detectors, sensitivity to reactor neutrino oscillations at several tens of kilometer standoff.

The same types of detector could enable discovery, exclusion or monitoring of nuclear reactors at standoff distances from one to as many as several hundred kilometers. With sufficient suppression of backgrounds, remote detectors (25-500 km standoff) on the 50-kiloton to one-megaton scale would provide a 25% statistically accurate measurement of the power of a 10-MWt reactor in several months to a year [?].

Water Cherenkov detectors are one promising approach to achieving detector masses on the scale required to meet the above physics and nonproliferation goals. While the water Cherenkov approach is currently disfavored in the United States' LBNE planning process, it nonetheless retains considerable interest for the global community, in particular in Japan [?].

To allow sensitivity to low energy antineutrinos through the inverse beta decay process, the water would be doped with gadolinium, so that final-state neutron can be detected by the ~4 MeV of measurable Cherenkov energy deposited in the gamma-ray cascade that follows capture of neutrons on gadolinium. Sensitivity to neutrons has already been demonstrated via this method in ton-scale detectors [?], and using a kilogram scale sealed Gd-water test cell inserted into the center of the large Super-Kamiokande water Cherenkov detector [?]. A logical next step is to show direct sensitivity to reactor antineutrinos in much larger detectors uniformly doped with gadolinium. A kiloton-scale demonstration of this detector type is now being proposed by the WATCHMAN collaboration in the United States [?]. Such a demonstration would serve to integrate and exercise many of the required components of 100 kiloton and larger detectors. These components include the ability to recirculate water with gadolinium present, the preservation of the long attenuation length for Cherenkov light in gadolinium doped water, the use of next-generation flat panel PMTs, or wavelength-shifting plates to reduce deployment costs. A purpose-built detector of this kind, deployed a few kilometers from a reactor,would satisfy the NNSA mission of demonstrating remote reactor monitoring. It would also be the only supernova detector operational in the United States, competitive with only a handful of existing detectors worldwide.

Several-hundred-kilometer standoff detection of antineutrinos from high power (GWt) reactors is already possible using liquid scintillator technology. This has been clearly established by the KamLAND detector [?], sensitive to antineutrinos from civil power reactors throughout Japan, and with a few-percent flux contribution from reactors in South Korea, 400 kilometers away. Despite this remarkable achievement, significant additional work is needed to make the detectors sensitive to the few hundred-fold lower power reactors of greatest interest for nonproliferation.

Scaling of pure liquid scintillator designs such as KamLAND or Borexino is another approach to megaton class detectors. This approach is exemplified by the LAGUNA collaboration in Europe [?]. Because of their higher light output, liquid scintillator detectors likely would not require a neutron capture agent, and would achieve some cost savings through reduced photomultiplier tube requirements compared with water Cherenkov detectors. However, the cost of raw material and the environmental hazards would be higher, and further study is need to determine whether the required attenuation lengths and radio-purity can be achieved.

1.10.5 Application of Neutrino-related Technologies

A high degree of synergy is evident in technology developments related to neutrino physics experiments. The size and scale of the detectors and instrumentation needed, as well as the novel accelerator specifications, draw on the creativity of many communities to address and solve the challenging problems encountered. The paradigm of close collaboration between Laboratory, University and Industry has been fruitful, solving immediate needs of the neutrino community, and providing spinoff applications in quite different fields with broad societal impact. Examples are provided in the following sections.

1.10.5.1 Detectors

Neutrino/antineutrino detection has motivated significant work on detection technology, the benefits of which extend well beyond the physics community. Examples include plastic and liquid scintillator doped with neutron capture agents, high flashpoint scintillators with reduced toxic hazards compared to previous generators of scintillator, and low-cost flat-panel photomultiplier tubes. Doped organic plastic and liquid scintillator detectors are now being pursued in the United States [?], as a means to improve sensitivity to the reactor antineutrino signal. The detectors exploit pulse shape discrimination techniques to distinguish between gamma-rays, fast neutrons and thermal neutrons. This is of evident importance for reactor antineutrino detection, where a key element of the signature is a thermal neutron, and for which gamma-rays and fast neutrons comprise significant backgrounds. This capability is immediately relevant in nuclear security contexts, because there is a strong need for improved detectors capable of such particle discrimination in the areas of nuclear search, treaty verification and monitoring of fissile materials. In such applications, the signal and backgrounds consist of the same three particle types - gamma-rays and fast and thermal neutrons, with subtle time correlations that are somewhat analogous to those produced in antineutrino interactions. Moreover, for the nonproliferation and arms-control applications, large-solid-angle detectors on the scale of hundreds of kilograms to tons are required in order to intercept coincident-multiple-neutron and gamma-rays arising from the same fission or fission chain in quiescent nuclear material. As a result, breakthroughs in scintillator development for neutrino detection clearly benefit nuclear materials security, and vice-versa. In a similar way, companies such as Bicron Technologies and Eljen Technologies have devoted resources to reducing the biohazards and improving the optical clarity of their scintillation cocktails, in order to facilitate neutrino detection. These improvements clearly benefit other customers, such as the medical and pharmaceutical communities, which use scintillator detectors for radio-assay in nuclear medicine applications. The overall product lines of these companies have benefited considerably from research that has focused on making better neutrino detectors. Another area of research with important spinoff potential is the development of low cost, high efficiency photomultiplier tubes. Cutting edge research that focused on low-cost PMTs is exemplified by the Large Area Pico-second Photo-Detectors project [?]. Beyond enabling lower-cost neutrino detectors at every scale, such detectors would lower costs and improve performance of medical imaging devices such as Positron Emission Tomography systems, for which the photo-detector element is often a dominant cost and critical component. Emerging nuclear security applications that demand PMT-based imaging, such as three-dimensional reconstruction of the locations and inventories of fissile material in a reprocessing or enrichment plant, also great benefit from lower-cost PMTs.

1.10.5.2 Accelerator

A recent PCAST report states [?] "The science of neutrino production demands creative new solutions for intense [accelerator-based] sources. These include high power synchrotrons such as the Main Injector, high power high energy superconducting LINACS such as the Oak Ridge Spallation Neutron Source and the future Project-X, powerful new ways of generating intense beams such as DAEδALUS, and other ideas." The spinoffs with broad technological impact from advanced accelerator development are numerous and spectacular: advances in engineering with superconducting materials and magnets, high-volume cryogenics, sophisticated control systems and power converters, one could go on and on. A very direct connection with neutrinos, however, is provided by the DAEδALUS project. Based on a cascade of compact cyclotrons capable of sending multi-megawatt beams onto neutrino-producing targets, this concept pushes the performance of cyclotrons to new levels. Development of this technology, based on accelerating H_2^+ ions, is being pursued by a broad collaboration of US and foreign laboratories, universities and industry. Khrishnan Suthanthiran, President of TeamBest, one of whose subsidiaries markets isotope-producing cyclotrons, states, "[The] original motivation for the device is for it to become the injector for a very high intensity neutrino source for pure science research (DAEδALUS). The same concepts you have described have an immediate medical radioisotope application." One of the test prototypes being developed with the assistance of Best Cyclotron Systems Inc. is a 28-MeV cyclotron designed for H_2^+ injection studies, but also suitable for acceleration of He^{++}, and directly applicable to the production of ^{211}At, a powerful therapeutic agent whose " use for [targeted α particle therapy] is constrained by its limited availability." [?]. The development of these compact, high-power and relatively inexpensive cyclotrons is expected to have a profound impact on many fields, ranging from neutrino physics and isotope production to ADS applications such as driving thorium reactors or burning nuclear waste [**?**].

1.10.6 Education and Outreach

1.10.6.1 Educating Physicists about Nonproliferation

In order to reach out to the public effectively, physicists themselves should be made aware of the potential utility of neutrinos for nuclear security. The natural overlap in signal and technology between reactor monitoring for nonproliferation and reactor oscillation experiments already helps prepare physics students and post-docs for work on nuclear security research. In a similar way, dark matter experiments provide a useful education in nuclear security technology, inasmuch as the keV-MeV-scale interactions of possible dark-matter candidates are strongly analogous to the interactions induced by the neutrons and gamma-rays emitted by quiescent nuclear material. Detectors for these latter particles are the focus of a large scale domestic and international effort within government laboratories, academia (mostly nuclear engineering departments) and industry, and are used in a range of nuclear screening, nonproliferation and treaty verification applications. As revealed by the growing field of applied antineutrino physics, awareness of these connections has grown over the last ten years in the physics community. However, relatively few physicists - including many actively engaged in applied research - have much if any formal education in the structure of the global nonproliferation regime, or in the history of the atomic era that led to the current state of affairs in nuclear security. This is especially unfortunate, since at least in the United States, this history is closely intertwined with the development of the large scale accelerator and underground experiments that employ many of these same physicists. In the last five years or so, a few physics departments, such as UC Davis, Virginia Tech, and others have worked to develop courses that introduce physicists to both the relevant technology and policy of nonproliferation and nuclear security. Nuclear Engineering departments have a closer connection to the nonproliferation regime, and many, such as MIT, UC Berkeley, Penn State, Texas A & M, and others, have developed explicit course elements targeting the connection between nuclear security and nuclear science. Indeed, many of these nuclear engineering departments have a strong research presence in the relevant overlapping areas of neutrino (and dark matter) science.

1.10.6.2 Educating the General Public about Neutrino Science

An aware and enthusiastic general public is the best way to ensure support and funding for basic research. Our work is supported by tax dollars, and the level of support depends in part on convincing both Congress and the taxpayer that their money is being spent wisely. To this end, the challenge of the neutrino community is to make the case that investments in our field are of benefit to the nation.

Each one of us should accept our responsibility for conveying this message whenever possible. Opportunities for this are more frequent than one would imagine: addressing local Rotarians, Kiwanis or other public service groups (who seem always to be looking for speakers); discussions in local school science classes; organizing field trips to labs or research centers, to give a few examples.

Neutrino physics offers a wealth of fascinating and counter-intuitive concepts (e.g. oscillations, high fraction of the Sun's energy emitted as neutrinos, and extremely low cross sections enabling neutrinos to easily penetrate the Earth). (In regards to the faster-than-light controversy, an object lesson should be learned of carefully managing potentially contentious information, and considering the consequences of its release prior to a thorough vetting by independent experts, lest it damage the credibility of the field. While the controversy did bring neutrinos into the limelight for a brief time, the adage of any publicity being good publicity emphatically does not apply to our field. It is far preferable to accurately and conservatively report and review results, especially such extraordinary claims.) In addition, our field sports some highly photogenic experiments (e.g. IceCube, Borexino, Super-K). A suggestion could be made that a reservoir of material be collected, updated and made available for persons to use in outreach talks and activities: lecture outlines, lists of talking points, graphics, etc. CERN and FNAL provided an example of this type of collection in the material they assembled in support of their international outreach effort for hosting public-outreach lectures on anti-matter coordinated with the release of the Angels and Demons blockbuster film.

The interesting practical applications of neutrinos described earlier for reactor monitoring and non-proliferation treaty verification, as well as programs studying geoneutrinos in relation to understanding the heat dynamics of the interior of the Earth, provide highly relevant and compelling topics to be communicated to the public.

The importance of Education and Outreach is recognized in the establishment of a whole (Snowmass) "Frontier" dedicated to this topic. Our community should embrace this effort, looking for ways of coordinating and contributing to their activities for furtherance of our mutually compatible goals.

1.11 Conclusions

The Standard Model has been one of the most successful theoretical descriptions of Nature in the history of humankind. Decades of precision tests have revealed only one concrete violation of the Standard Model: the existence of non-zero neutrino mass. While many experiments continue to look for other Standard-Model-violating processes, it is clear that continued study of the neutrino sector is of the upmost importance.

Compared to the other fermions, the elusive nature of the neutrino has made it extremely difficult to study in detail. While the field of neutrino physics has been making continuous progress over many decades, the rate of progress in recent years has been impressive. The current generation of neutrino experiments is producing important results that help us to better understand the neutrino sector. In some cases, these experiments have uncovered intriguing anomalies that require additional study and will prompt future experiments. Furthermore, the current generation of neutrino experiments is providing advances in detector technology and analytical techniques needed for the next generation of neutrino experiments.

This synergy − the physics of the neutrino as a key to understanding the fundamental nature of the physical world, along with technological advances in experimental techniques − make this an exciting time for neutrino physics. The coming decade will provide us with an opportunity to answer some of the most fundamental and important questions of our time: Are neutrinos Majorana or Dirac particles? Is there CP violation in the lepton sector? Does the small, but non-zero neutrino mass couple to a mass scale that is far beyond what we can hope to reach in colliders? Although these questions have been asked for many years, we now have opportunities to finally answer some of them.

The coming decade promises significant experimental progress around the world. In the search for neutrinoless double-beta decay, a number of experiments rely on complementary isotopes and experimental techniques. The next generation of $\sim$100 kg-class $0\nu\beta\beta$ experiments should reach effective masses in the 100 meV range; beyond that, there are opportunities for multi-ton-class experiments that will reach $<$10 meV effective mass sensitivity, pushing below the inverted hierarchy region. The next-generation tritium beta decay kinematic experiment, KATRIN, will push limits a factor of 10 beyond the current best ones; innovative new ideas may help to go beyond. Long-baseline neutrino oscillation experiments will clarify the neutrino mass hierarchy and search for CP violation; these require new high-power beams and large underground detectors. Both T2K and MINOS are currently running, with NOνA expected to begin in 2014. Reactor experiments will also continue to take data this decade. There is vigorous worldwide activity towards planning for large-scale next-generation long-baseline efforts. There are exciting opportunities for the US to take leadership in this arena with LBNE, and beyond that, Project X, for increased neutrino intensity at several beam energies. Given the challenges associated with precision measurements in the neutrino sector, complementary baselines, sources and detector techniques will be needed to help further understand the nature of CP violation in the neutrino sector. Smaller experiments will also help address some of the remaining anomalies and hints for new physics beyond the three-flavor paradigm.

The diversity of physics topics that can be probed through the neutrino sector is significant, and the interplay between neutrino physics and other fields is vast. Neutrinos can and will provide important information on structure formation in the early universe; Earth, solar and supernova physics; nuclear properties; and rare decays of charged leptons and hadrons. In other words, the neutrino sector sits at the nexus of the worldwide effort in energy, intensity and cosmic frontier physics.

Finally, the unique physics potential and technological advancements have conspired to produce a fertile environment for new ideas for improved measurements and new techniques. This provides an important training ground for the next generation of scientists and engineers, motivated and excited about ground-breaking experiments that can benefit from their contributions.